Journal of Environmental Management 286 (2021) 112141

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Agrochemical pesticide production, trade, and hazard: Narrowing the information gap in Colombia

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ARTICLE INFO

Keywords:
Low and middle income countries
Human health
Ecotoxicity
Highly hazardous pesticides
Acute toxicity

ABSTRACT

Pesticides are a major tool for the intensification of agriculture, and helped to increase food, feed and biofuel production. Yet, there are persistent concerns about the negative effects of pesticides in human health and the environment, particularly in low and middle income countries (LMICs). Given the lack of information on pesticide exposure and hazard, Colombia exemplifies the need to narrow the information gap on pesticide risk in LMICs. We assessed pesticide hazard in Colombia based on the official toxicity categorization, compared it to more integral international standards, and identified main actions to narrow this information gap. Results showed that Colombia has been a relevant regional actor in pesticide production and trade, reaching almost 75 million kilogrammes and liters sold in 2016. Based on acute toxicity for humans, a quarter of the amount of pesticides sales and imports, and a third of the exports in 2016 ranged from moderately to extremely toxic. The top-selling agrochemicals in 2016 (glyphosate with 14% of the total sales, chlorpyrifos 7.5% and mancozeb 6.9%) are also commonly used in other countries, reflecting a homogenized global industry. Compared to integral international categorizations, we found that for that year 63% of the pesticides sold with slightly acute toxicity are actually considered highly hazardous pesticides (HHP) for humans or the environment, evidencing the need to use a more integral hazard categorization in the country. Narrowing the information gap in pesticide use and associated risks demands a transparent process of knowledge creation and sharing, including funtional information and monitoring systems. This should be part of an integral assessment and regulation that better defines HHP, their production and trade to reduce pesticide risk while informing a transition towards sustainable food systems.

1. Introduction

Pesticides are a major tool to protect crops from pests and help to increase agricultural intensification, and the production of food, feed and biofuel across the globe (Carvalho, 2006, 2017). Pesticides are also frequently used to suppress weeds in other land uses (e.g. flower production and lawns), and to control vector-borne diseases (WHO 2011). At the same time, for more than six decades there have been persistent concerns about the negative effects of (mis)using pesticides in human health and the environment (e.g. Kingsley 1956; Johnson 1968; Pimentel 1972; Pimentel and Edwards 1982; WHO 1990; Ecobichon 2001; Fantke et al., 2012; Bourguet and Guillemaud 2016). These concerns range from Carson's arguments of the devastating effects of DDT on humans and the environment from the 1960's (Carson 1962), to more recent studies relating the (over)use of neonicotinoids to the collapse of some animal populations such as bees and birds (Blacquière et al., 2012; van Lexmond et al., 2015; Li et al., 2020).

Risk assessment of the impact of pesticides on human health and the environment depends on: exposure (i.e. duration and use levels), hazard (i.e. toxicity and persistence of the pesticides used), and the environmental conditions where pesticides are applied (Damalas and Eleftherohorinos 2011; FAO and WHO, 2016). Despite progress in national and international regulation (Hagen and Walls 2005; Pelaez et al., 2013; Möhring et al., 2020), there remain considerable information gaps and uncertainties on pesticide risks, particularly for low and middle income countries or LMICs (Eddleston et al., 2002; Dinham 2003; Kesavachandran et al., 2009; Schreinemachers and Tipraqsa 2012; FAO and WHO, 2019). Compared to high income countries, in LMICs there are relatively

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https://doi.org/10.1016/j.jenvman.2021.112141
Received 30 September 2020; Received in revised form 4 February 2021; Accepted 4 February 2021
Available online 3 March 2021

more people working on agriculture, with higher poverty rates, lower education and knowledge on pesticide risk, less protective equipment, and larger gap between prescribed instructions and actual use. Besides, in LMICs there is lack of functional monitoring systems, higher use of highly hazardous products (HHP) that are older and off-patented (i.e. relatively cheaper), poorly functioning registration schemes, perceptions that poor farmers need cheap pesticides, and lack of knowledge about alternatives (FAO and WHO, 2016) . Finally, many LMICs are in the tropics and host biodiversity-rich regions, and in terms of agrochemicals have different needs, mobility, degradation and risk compared to temperate countries, indicating that knowledge produced in temperate environments to inform the environmental risk assessments supporting pesticide registration processes needs to be adapted to tropical conditions (Sanchez-Bayo and Hyne 2011; Lewis et al., 2016; Gentil et al., 2020).

Narrowing basic information gaps on pesticide risk is fundamental for multiple reasons: developing information and monitoring systems on pesticide (mis)use; identifying vulnerable communities and ecosystems; mitigating the negative effects of pesticide mis(use); empowering farmers, civil society and other relevant actors in the transitions to more healthy agri-food systems; and informing policy making to better regulate pesticide production and use, among others. Colombia exemplifies the necessity to narrow this information gap in LMICs. First, Colombia produces and exports pesticide products to different countries from Ecuador to Japan. The agrochemical industry was established in the second half of the 20th century with foreign investment, being dominated by few multinational manufacturers (DNP 2019). By 2018, it provided almost five thousand jobs —0.4% of all the jobs of the national production chains–, and generated 68 million US dollars in exports –nearly 2% of the export value of the national productive chains (DNP 2019). Second, the country uses and imports considerable amounts of pesticides and raw materials (Lee and Espinoza 1998). FAO estimates suggest that Colombia used more than 37.7 thousand tons of pesticides in 2018, ranking 18th on the top pesticide users worldwide (dataset FAO 2020). Although there is no consolidated information linking agricultural production and pesticide use in Colombia, early descriptive data based on crop area and intensification level mentioned major agricultural systems demanding the highest amount of pesticides, including: mechanized and irrigated rice production; agro-industrial banana cultivation largely for export; intensified potato production mainly by smallholders; greenhouse flower cultivation largely for export; bean production mainly by smallholders; coffee production largely by smallholders and for export; and agro-industrial sugar cane and oil palm cultivation (Bonilla-Arboleda et al., 2000). Pesticide use in Colombia also included the excessive and large-scale spray of herbicides done by the government to eradicate crops of illicit use in important biodiversity hotspots (Solomon et al., 2007; Camacho and Mejía 2017).

Third, the Colombian government has attempted to control, monitor and promote the production and use of agrochemical pesticides with national, regional (i.e. Andean Community of Nations or CAN) and international agreements and regulations since the 1970's (see Box 1 and 2); but their success has been limited. CAN also delineates major pesticide regulation for each of its country members (i.e. Bolivia, Colombia, Ecuador, Peru). However, some organochlorine pesticides that have been banned in the past are still being used (Varona et al., 2010; IDEAM 2019), evidencing limitations to enforce current regulations. Fourth, there is evidence of the negative effects of pesticide (mis)use in Colombia. Studies have reported cases on the negative pesticide impact in human health (e.g. Restrepo et al., 1994; Idrovo 1999; Cárdenas et al., 2010; Varona et al., 2010; 2012; Díaz-Criollo et al., 2020), food and the environment (e.g. Murcia and Stashenko 2008, Tobón-Marulanda et al., 2010).

Lastly, although some studies have described patterns of pesticide production and sales in Colombia (e.g. Herrera-Rojas and Polanco-Rodríguez 1995; MADS 2008; IDEAM 2019), information on exposure and hazard remain limited and fragmented. Specifically, agrochemical companies provide annual statistics of production and trade per product to the Colombian Agricultural and Livestock Institute (ICA), who is responsible for organizing and making this information partially available without publishing confidential data on specific products. These data are published annually in multiple tables and levels (e.g. country, active ingredient, product, company) without clear identifiers hampering data combination and analysis. From 2010, the levels of pesticide residues are monitored in selected crops prioritized based on their harvested volume and previous evidence of pesticide residues (INVIMA, 2017). This monitoring includes major imported, exported and consumed crops such as potato, pineapple, tomato, avocado, orange, and onion; but excludes other major crops such as coffee, banana, plantain, sugar cane, oil palm, and managed grasslands (INVIMA, 2017). The National Health Institute (INS) also runs an epidemiological surveillance programme for organophosphates and carbamates, and a surveillance protocol to monitor human pesticide poisoning (PAHO et al., 2006). Finally, a national policy covers the monitoring of water quality without explicitly including pesticide residues (MADS, 2010).

All the reasons mentioned above emphasize the need to narrow the information gap on pesticide risk in Colombia. This study aims at assessing the potential hazard levels in the production and trade of pesticides in Colombia based on current official categorization, and comparing it with more integrated standards. The first part of the paper focuses on pesticide hazard based on acute toxicity for humans to understand trends and current patters of pesticide production and trade according to the official pesticide categorization and regulatory framework in Colombia. The second part of the paper focuses on pesticide hazard based on a more integral definition and international standards including potential pesticide effects on acute toxicity and chronic health for humans and the environment. Given the general lack of consolidated knowledge in the country and similar LMICs, this assessment is a basic step to both: generate more structured evidence on the current state of affairs of pesticides in countries that produce, export and import these products; and to identify specific gaps to consolidate more transparent and integral information systems to take informed decisions on pesticide registration and regulation in Colombia.

2. Methods

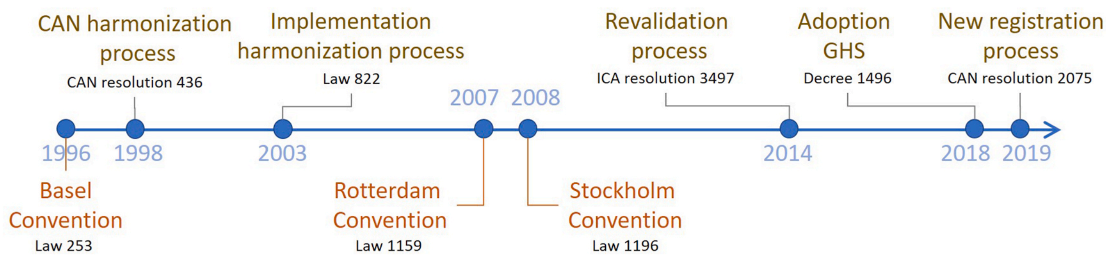
2.1. Data collection & analysis

Official data on pesticide categorization, production and trade was retrieved on early 2020 from the ICA website.[1] Pesticides included mostly fungicides, herbicides and insecticides, with some raticides, acaricides and raw materials for pesticide production. Two main data sources were available: a first set of tables at pesticide product level with information on acute toxicity category, main active ingredients, validity category, and year of registration or revaluation (see Box 1); and a second set of tables at active ingredient(s) level with annual information on the amount of pesticide production, sales, imports and exports (in liters and kilograms) per agrochemical company, country of origin/destination and main use (e.g. insecticides, herbicides, fungicides). Data on pesticide production ranged between 2008 and 2016, while data on imports and exports with detailed information linking countries and active ingredients were available for only two years (2008 and 2016). A central database was created combining these two data sources, including acute toxicity category, pesticide production, sales, import, export and origin/destination countries, and main use.

Two main assumptions/simplifications were needed to consolidate this central database. First, pesticide active ingredient(s) was selected as the identifier because it was the only common variable present across tables. As a result, misspellings and multiple naming had to be

[1] Data available at https://www.ica.gov.co/areas/agricola/servicios/regulacion-y-control-de-plaguicidas-quimicos.aspx.

Box 1
Main pesticide regulations in Colombia



Since 1998, CAN has introduced regulatory frameworks and manuals to harmonize processes of pesticide registration and control (CAN Decision 436, 1998), implemented in Colombia through the Law 822, 2003. Colombia also signed and ratified the multilateral conventions of Basel (Law 253, 1996), Rotterdam (Law 1159, 2007) and Stockholm (Law 1196, 2008) aimed at informing about, limiting and dealing with the waste, trade, and use of some hazardous chemicals (López et al., 2012). In 2014, as a requisite to become its member, the Organisation for Economic Co-operation and Development (OECD) recommended Colombia to adopt the Globally Harmonized System of Classification and Labelling of Chemicals or GHS (Hoyos-Calvete, 2017; UN, 2019). That same year through the ICA Resolution 3497, a revaluation and re-registration process of pesticide products licensed before 2003 was relaunched to upgrade old products to new registration standards stipulated by CAN (ICA, 2014), filtering out hundreds of outdated pesticides that did not meet current standards or were not presented again for registration after 2014. In 2018, Colombia officially adopted the framework of the GHS (Ministry of Labour, Decree 1496) and, in 2019, the CAN (Resolution, 2075) approved new pesticide registration and labelling guidelines for its member states to continue transitioning within the next 5 years to the GHS (CAN, 2019).

Box 2
Current pesticide registration requirements in Colombia

To register a pesticide product, chemical companies develop and present assessments to governmental offices, which evaluate this information. Companies provide, for both the main active ingredient and the final mixture of the product: a. An environmental risk assessment, to be evaluated by the Ministry of Environment and Sustainable Development; b. A human toxicology risk assessment examined by the Ministry of Health and Social Protection; and c. An efficacy assessment, analysed by ICA, which also conducts a final evaluation and registration of the product. Hazard classification is made in light of pesticide acute toxicity categories based on the following World Health Organization (WHO) human toxicity classes: I. extremely and highly toxic, II. moderately toxic, III. slightly toxic and IV. practically nontoxic. These categories are mainly defined based on the oral or dermal Median Lethal Dose or LD_{50}, which is the dose that kills half of the test animals (often rodents). For example, the threshold for category I for oral LD_{50} is ≤ 50 mg/kg, while >5000 mg/kg for category IV. Environmental concerns of an accepted product are addressed and mitigated by implementing an environmental management plan, training, and/or by including warning information on application and protection in the product label (ICA, 2003).

accounted for to join the tables (Annex Supplementary Material I). Additionally, because data on toxicity and concentration of active ingredients was at the product level (while production and commercialization data were at the active ingredient level), some of this information was excluded. To partly address this data loss, the most frequent toxic category was used to calculate the amount of pesticide produced or traded for active ingredients with more than one acute toxic category. Data on toxicity categories were derived from the product lists published between 2017 and 2019, which are only based on WHO acute toxicity for humans (see Box 2). On the other hand, entries with a combination of active ingredients and with available data on toxicity category were kept together given the potential difference in properties of the final mixture (Evans et al., 2015; Bopp et al., 2019). Second, a single measurement unit was calculated (kg|l) to sum data on either kilogrammes or liters, facilitating data presentation and analysis.

ICA data were analysed in four different ways to assess pesticide hazard in Colombia based on the current official toxicity categorization, pesticide production, and trade. First, to contextualise changes in total pesticides sales in the country, the relative change of pesticide sold between 2011-2013 and 2014–2016 was calculated and then compared to EU countries, which have these available data (EEA, 2018). Additionally, production and sales data (2008–2016), and amount of pesticides imported and exported to specific countries (2008 and 2016) were plotted to understand trends on pesticide hazard based on the official toxicity categorization. A description on the (relative) number of cancelled and revalidated pesticides products was also conducted to analyse the effect of the recent revalidation process in pesticide hazard. Finally, top-selling active ingredients were identified to better understand the hazard associated with recent pesticide sales in the country. These ingredients were selected based on the amount of pesticides sold (kg|l) in 2016 for each main use (i.e. fungicides, herbicides and insecticides). Then, for each ingredient, it was identified whether it was still a licensed product by early 2020, its acute toxicity category, whether it was part of the HHP list (see below), and the chemical group according to the Fungicide, Herbicide or Insecticide Resistance Action Committees (F/H/IRAC).

To compare this official toxicity categorization to more integral international standards, the ICA categorization of sales in 2016 was compared to the HHP list published by the Pesticide Action Network (PAN), a civil society organization promoting the effective international

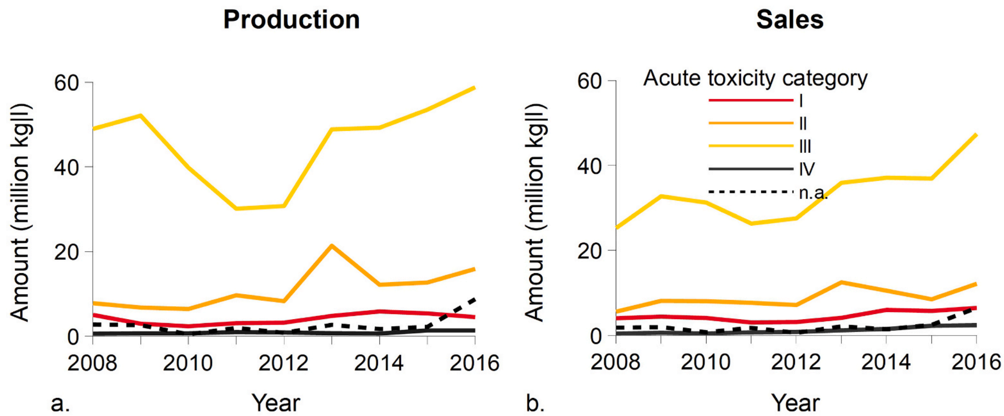


Fig. 1. Reported amounts of pesticide products produced (a.) and sold (b.) in Colombia between 2008 and 2016, including the toxicity category. Category "n.a." (not applicable) refers to raw materials with undefined toxicity category. The measuring unit (kg|l) is the sum of kilogrammes and liters. Data source: ICA.

action on the elimination of hazardous pesticides (PAN, 2019). Besides acute toxicity, the PAN list includes data on: long term (chronic) health effects for humans, environmental hazard criteria (e.g. toxic products for bees, aquatic organisms and/or very persistent in water and soils) and international regulations such as the Stockholm and Rotterdam Conventions (PAN 2019). The PAN list complemented the Joint FAO/WHO Meeting on Pesticide Management list by adding pesticides with potential endocrine disrupting properties, eco-toxicological properties and inhalation toxicity recognized by the European Union (EU), the US Environmental Protection Agency (EPA) and the International Agency for Research on Cancer (IARC), among others. The active ingredients of the PAN list were also included in the central database to be able to combine and compare it with the ICA data.

3. Results

3.1. Hazard based on acute toxicity categories

The amount of pesticides sold in Colombia almost doubled in less than a decade from a total of 37 million kg|l in 2008 to 75 million in 2016 (Fig. 1b). In fact, there was a 39.2% relative increase of agrochemical pesticides sold between 2011-2013 and 2014–2016. On the other hand, based on the official categorization of acute toxicity for humans, Colombia produced and sold considerable amounts of extremely, highly, and moderately toxic products between 2008 and 2016 (Fig. 1). Around three quarters of the pesticides produced and sold between 2008 and 2016 were products classified as slightly toxic (III), while the amount of highly hazardous products (extremely and highly hazardous or I, and with moderately acute toxicity or II categories) accounted for 20–25% of the total production and sales (Fig. 1). Differences in the amount of pesticide production and sales can be caused by imports, exports, and the time needed to sell the product.

Colombia was both the origin, transfer and destination of hazardous pesticides (Fig. 2). Imports of pesticides products and raw materials increased from 49 million kg|l in 2008 to 63.8 million kg|l in 2016. The USA and China were the origin countries of the largest amounts of agrochemicals imported in 2008 (21.4 million kg|l) and 2016 (35.6 million kg|l). In 2016, a quarter of the imports (16.2 million kg|l) were highly hazardous products (categories I and II), of which 11 million kg|l came from China, India and Panama. Around a third of all imports in 2008 (18.8 million kg|l) and 2016 (20.3 million kg|l) were raw materials for the production and processing of new pesticide products, particularly those coming from the USA. At the same time, exports decreased from almost 47.7 in 2008 to 43.7 million kg|l in 2016; in each of those same years Colombia sent around 30 million kg|l of pesticide products to Latin America and the Caribbean. Yet, the USA (4.4 million kg|l), Israel (3 million) and Poland (2.9 million) became major recipients of pesticide products in 2016. That same year, a third of the exports (15.2 million kg|

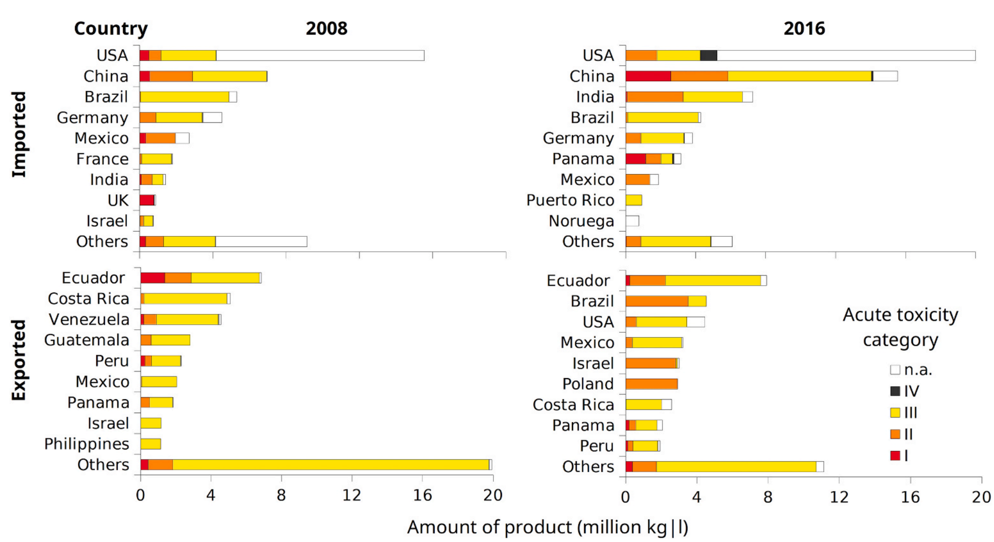


Fig. 2. Reported amounts of pesticide products imported to and exported from Colombia in 2008 and 2016, including countries and toxicity category (hazard). n.a. Not applicable because they were raw materials. The measuring unit (kg|l) is the sum of kilogrammes and liters. Data source: ICA.

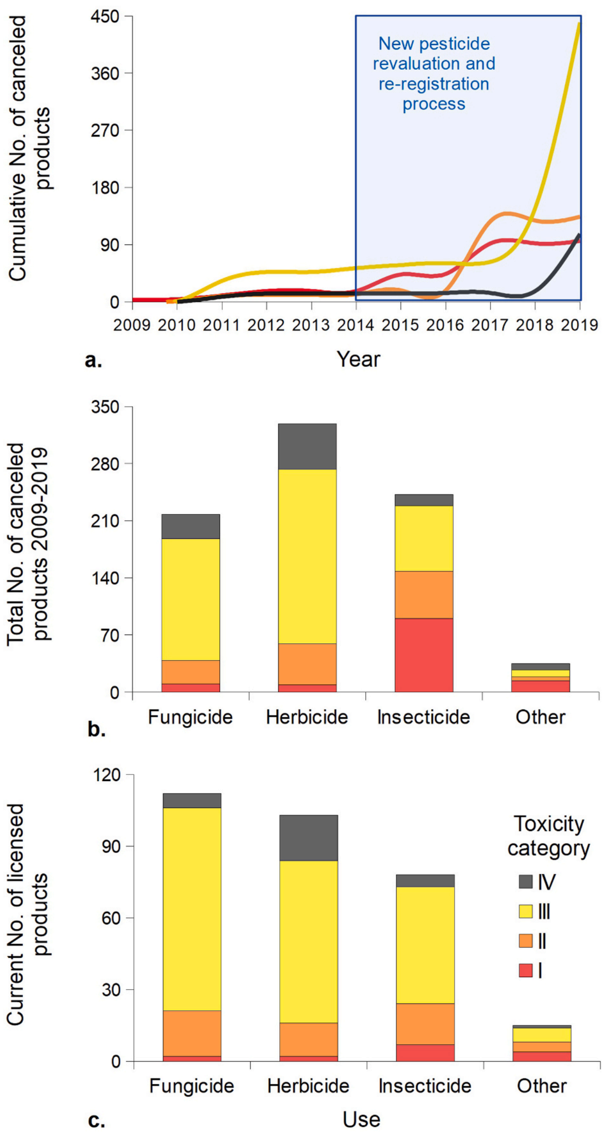


Fig. 3. Reported pesticide products and toxicity categories (hazard) related to: a. Number of cancelled products in the last decade. The shaded area signals the implementation of the new process of registration; b. Number per main use of the cancelled products between 2009 and 2019; and c. Number and main use of licensed products in 2019. Other uses combined bactericides, acaricides and growth regulators. Data source: ICA.

l) were hazardous products (acute toxicity category I and II), of which Colombia exported 11 million kg|l to Ecuador, Brazil, Israel and Poland. Between 3 and 30% of the total exports did not specify a country of origin/destination.

3.2. Effects of the revaluation process in pesticide hazard

The recent revaluation process launched in 2014 had a clear effect on the amount of cancelled products and their hazard level (Fig. 3). From over a thousand pesticide products, more than 700 outdated products were cancelled. Yet, almost 70 hazardous products (categories I and II) are still registered (Fig. 3a, Annex II). More than half of the cancelled products belonged to the category III, while 30% were hazardous products (category I and II). 40% of the cancelled products were herbicides while 56% of the insecticides were hazardous (Fig. 3b). Out of the currently valid pesticide products, 22% are hazardous (category I and II). Similarly, 36% of the valid pesticide products are fungicides, 33% herbicides and 25% insecticides (Fig. 3c).

3.3. Top-sales pesticides in 2016

A handful of often broad-spectrum agrochemicals dominated the amount of pesticides sold in Colombia (Fig. 4). In 2016, the top-10 herbicide active ingredients represented 50% of the total pesticide sales, wherein glyphosate was by far the most sold pesticide with almost 14% of the total sales, followed by chlorpyrifos (7.5%) and mancozeb (6.9%). The last two, along with paraquat, are hazardous pesticides (highly and moderately toxic categories) in the PAN list, and still valid in Colombia by 2019. All insecticide active ingredients were also listed by PAN as HHP, while only 5 fungicides and 4 herbicides were included in this list. By the end of 2019, twelve of these active ingredients did not correspond to any registered product by ICA, indicating that they were excluded during the revalidation process. For insecticides, there was a prevalence of organophosphate and carbamate chemicals.

3.4. Highly hazardous pesticides: beyond acute toxicity

Many products approved by the ICA fell into the PAN HHP list (Fig. 5). By the end of 2019, these included half of the 300 ICA registered products, which contained 54 active ingredients (see Annex III). Out of these, 17 products belonged to more than one hazard group: lambda-cyhalothrin belonged to 3 (acute toxicity, long term effects and environmental toxicity), while other 16 active ingredients belonged to 2 hazard groups. In total, at least 20 registered pesticide products are listed in the Rotterdam convention - Annex III of banned or restricted chemicals (i.e. alachlor, benomyl and paraquat). Nearly three quarters of the currently valid 54 active ingredients could have long term effects on human health (Fig. 5a), while a third of them could be an environmental hazard (e.g. toxic products for bees, aquatic organisms and/or very persistent in water and soils). Specifically, most of these PAN HHP fell into the ICA toxicity category III, accounting for 63% of the total amount of products sold in 2016 for this category. In contrast, there were 27 and 43 PAN HHP in the ICA's toxic categories extreme and high (I), and moderate (II), representing a quarter and more than a third, respectively, of the total amount of products sold in 2016 for these categories. In terms of main use, more than three quarters of the insecticides, half of the fungicides, and a third of the herbicides sold in 2016 were PAN HHP. Finally, while 92% of the active ingredients with environmental hazards were insecticides, 46% of those with potential long term effects in human health were fungicides and 36% herbicides (Fig. 5b).

4. Discussion

4.1. Trends of pesticide hazard in Colombia

Results showed that Colombia has been a relevant regional actor in pesticide production and commercialization. After 2005, the amount of pesticides sold in the last decade has largely increased. Compared to 30 EU countries, for example, only Bulgaria reported a relatively higher increase in the amount of pesticides sold between 2011-2013 and 2014–2016 than Colombia (EEA, 2018). Similar trends in other LMICs have been attributed to reduced rural population, and the need to intensify food production to feed a growing global population (Ecobichon, 2001). Further research is needed to elucidate changes in food demand, land use and agricultural intensification in Colombia, and whether they drive changes in pesticides used in different agricultural systems.

The analysis in pesticide commercialization confirmed that the largest pesticide users across the world are often the largest exporters, namely US, China, India and Brazil. Yet, LMICs tend to import relatively more hazardous pesticides products than (and from) high-income nations (UNEARTHED and Public Eye, 2020), reflecting differences in the challenges and enforcement of effective regulations on pesticide use among these countries (e.g. Bhandari et al., 2019; Grung et al., 2015;

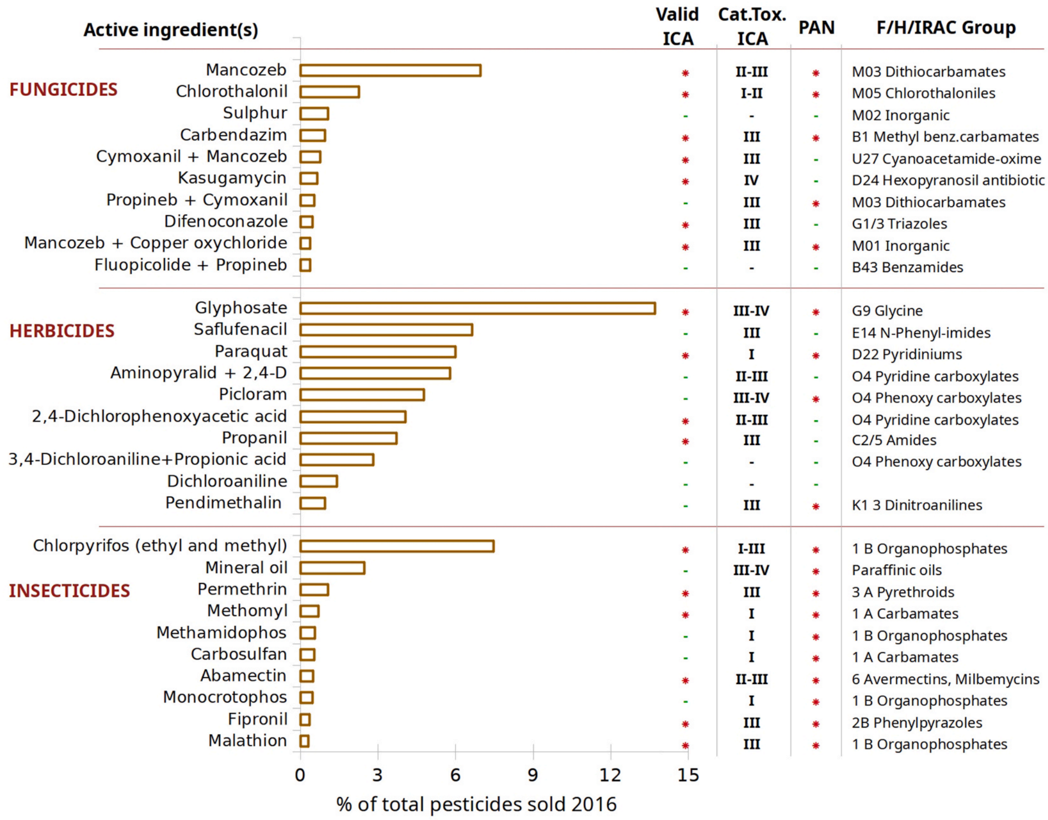


Fig. 4. Proportion of sales of the 10 top-selling fungicides, herbicides and insecticides in 2016 including whether they had currently licensed products (*), ICA toxicity category, whether they were part of the PAN's highly hazardous products (*), and group based on the F/H/IRAC. Data source: ICA, PAN and F/H/IRAC.

Zhang et al., 2011; Jardim and Caldas, 2012; Pelaez et al., 2013; Bourguignon et al., 2016; Donley, 2019; Trasande, 2017; Boone et al., 2014). In terms of imports to Colombia, further research could elucidate the reasons and final destination of increasing amounts of HPPproducts with acute toxicity coming from China, India and Panama; the potential hazard of raw materials coming mainly from the US; and the overall risk of imported pesticides that are formulated into new products and exported to other countries.

In terms of the exported products, although there were information gaps in the identity of the recipient countries, places outside Latin America were larger recipients of pesticides. Still, this study confirmed that Colombia is a relevant pesticide source for several Latin American countries, who often face similar challenges in terms of exposure to toxic products in vulnerable communities, power imbalances, poor governance, lack of adequate regulations and information gaps on pesticide risks (e.g. Wesseling et al., 2001a; Orozco et al., 2009; Bravo et al., 2011; Cole et al., 2011). For example, around a third of the volume and value of the pesticides imported to Ecuador in 2015 came from Colombia (Naranjo-Márquez, 2017). This suggests that additional research is needed to understand the risks of such a complex chain, where Colombia is at the same time a relevant user, importer and exporter of (hazardous) agrochemicals. Finally, the potential consequences of the trade of hazardous pesticides from and to Colombia reinforces the call to harmonize pesticide use and regulation globally (Braga et al., 2020).

4.2. Hazards in the top-selling active ingredients

Some of the identified top-selling agrochemical pesticides sold in recent years (i.e. 2,4-D, propanil, atrazine and mancozeb) were already commonly sprayed since the 1950's and 1960's in Colombia (Herrera-Rojas and Polanco-Rodríguez 1995). Additionally, the current top-selling products reflected consumption patterns in other countries, showing a globalized agrochemical industry. The most prominent case is glyphosate, a systemic molecule used to control a wide range of weeds in conventional and genetically modified crops (Mora-Oberlaender et al., 2018) whose commercialization has increased almost 15-fold globally from 1996 and it will probably remain the most common pesticide in the coming years (Benbrook, 2016). In Colombia, glyphosate was also sprayed to eradicate illegal crops between 1984 and 2015 (Lozano 2018), and there are currently discussions to reinitiate glyphosate aspersions (Idrovo and Rodríguez-Villamizar, 2018). The wide application of glyphosate has facilitated the rapid emergence of resistant weeds (Heap and Duke 2017), forcing the need for higher concentrations, more frequent applications, and combined used with other molecules such as paraquat and saflufenacil, increasing potential environmental risks (Benbrook, 2016; Dennis et al., 2016). Despite glyphosate has been classified in Colombia as slightly toxic (McComb et al., 2008), there are global concerns about its chronic effects and its breakdown products on the health of humans (IARC, 2015; Myers et al., 2016; van Bruggen et al., 2018; Portier, 2020), fish and amphibians (Braz-Motta et al., 2015; Van Bruggen et al., 2018). In Colombia, Camacho and Mejia (2017) reported that glyphosate exposure was associated with dermatological, respiratory illnesses and a greater number of miscarriages.

Paraquat is another top-selling herbicide that needs specific attention because of its high toxicity to humans. Paraquat is a low-cost chemical used for its rapid effect in the control of grasses and dicotyledonous weeds, and as a defoliant and desiccant in many crops (Bromilow 2004). Paraquat is classified as highly toxic to humans with proven acute and chronic effects (Wesseling et al., 2001a,b; Tsai 2013). While in the EU paraquat was banned in 2007 (EUR-Lex 2007) and its use is restricted in the USA (EPA, 2019), in Colombia and other LMICs with less stringent regulations paraquat poisoning is a major health problem for exposed workers, and people use it to commit suicide (Buendia et al., 2019; Wesseling et al., 2001a,b). Although paraquat can

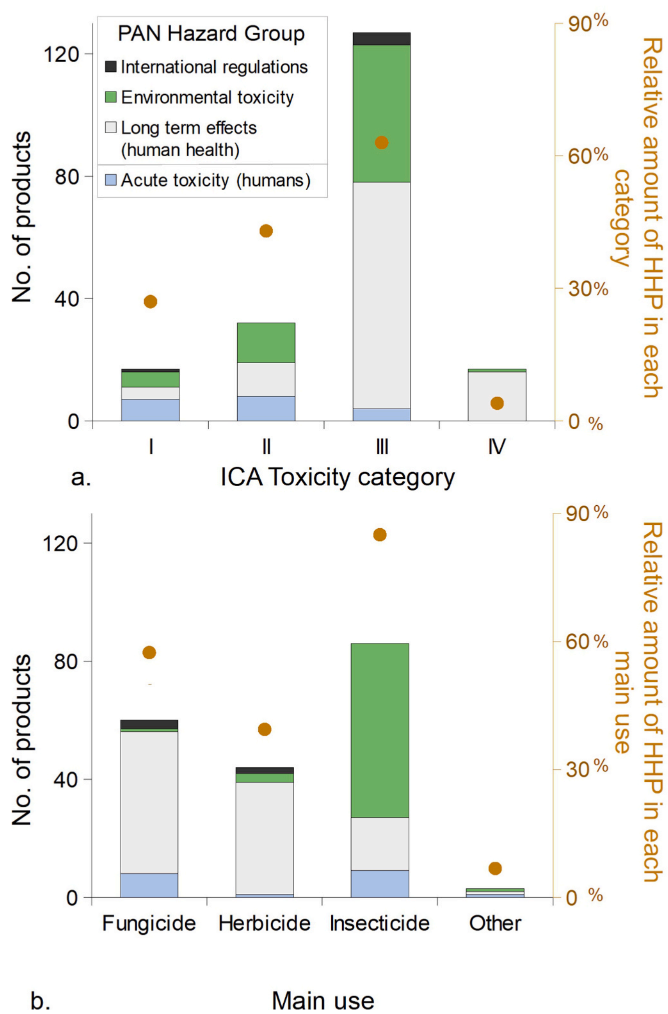


Fig. 5. Comparison between the ICA (acute) toxic categories and PAN-HHP including: a. Number of currently registered pesticide products whose active ingredient was considered a HHP and hazard group by the PAN per: a. ICA toxicity category; and b. Main use. Dots and second y-axis represented the % of these HHP in the sales for each individual toxicity category and main use in 2016. Data source: ICA and PAN.

be degraded by microorganisms, this is a slow process; due to its extensive use, it can accumulate in soil and water, increasing the risk of exposure for humans and other mammals (Huang et al., 2019).

Among fungicides, mancozeb was the most sold product in 2016, and is also a common product in many parts of the world. Mancozeb global market is growing because of its low cost, wide range of usage (Fungicides Market, 2019), and because it acts at different target sites in pathogens, making it less susceptible for pests to develop resistance (FRAC, 2020). Although mancozeb has been characterized as having low-acute toxicity in animal studies, it has been associated with chronic effects on human health (Belpoggi et al., 2002; Brody et al., 2013; Runkle et al., 2017; (Srivastava et al., 2012)). In Colombia, Benavides and Lozada (2016) showed that potato growers constantly exposed to mancozeb showed a higher prevalence of hypothyroidism. Mancozeb metabolites have also been found in water and soils, raising questions about its length of exposure and environmental risk (Alza-Camacho et al., 2016; Dominguez et al., 2009).

Insecticides generate major concerns in terms of hazard for human health and the environment. Most insecticide top selling products in Colombia are HHP (see section below); these molecules typically include organophosphates and carbamates, which have been widely used in both agricultural production and vector control of diseases since the 1950s (Herrera-Rojas and Polanco-Rodríguez, 1995). Although insecticides are responsible for a significant number of accidental and intentional poisonings, these molecules are readily available and poorly regulated, particularly in LMICs (Eddleston et al., 2002). Besides their devastating effects on non-target terrestrial and aquatic organisms (Chelinho et al., 2012, Eng., et al., 2017; Moreira et al., 2015), these molecules can be easily absorbed by the human body, causing well established chronic and neurotoxic effects in humans (Gupta 2004; Muñoz-Quezada et al., 2016). In Colombia, there is evidence of organophosphate and carbamate residues in food above the maximum allowed residue (MRL) limits considered safe for human consumption in the country (e.g. Varona et al., 2010; 2016; Murcia and Stashenko, 2008; Cárdenas et al., 2010), as well as of organophosphate exposure to non-target beneficial organisms such as bees (Rodriguez-Lopez et al., 2014).

Within insecticides, chlorpyrifos was the top selling active ingredient. This is an organophosphate used in numerous crops of economic importance to the country such as banana, rice, coffee and potato, among others. Increasing global concerns about its harmful effects on human health have led to recent restrictions or prohibitions of chlorpyrifos in different countries and some states in the US (EFSA 2019; Government of Canada, 2019; Hawaii SL, 2018; NYS Executive Chamber, 2019; CalEPA 2019). For example, human maternal exposure to chlorpyrifos has been correlated with smaller head circumference at birth and different neurobehavioral deficits (Bouchard et al., 2011; Rauh et al., 2011). Studies on environmental fate have shown that chlorpyrifos passes via air drift or surface runoff into natural waters affecting crustaceans and fishes that, when exposed to sublethal concentrations, exhibit oxidative stress, endocrine disruption, and acetylcholinesterase inhibition, among other effects (Duarte-Restrepo et al., 2020; Oruç, 2010; Palma et al., 2009). In Colombia, a study also found that chlorpyrifos was the most abundant pollutant in 68% of honey samples, with 4.9% of the samples above the MRL (Rodriguez-Lopez et al., 2014).

Global market participation of organophosphates is shrinking (from 43% in 1990 to 14% in 2008) because of their toxicity and pest resistance (Jeschke et al., 2011). They are being progressively replaced by neonicotinoids, systemic agrichemicals which are also effective for a wide range of insect pests, are less toxic to humans than organophosphates, and are widely used as seed coating treatments (Grout et al., 2020). Yet, neonicotinoids are persistent in the environment, neurotoxic to non-target species, and their large scale application has negatively impacted populations of key species such as bees and birds (Blacquière et al., 2012; van Lexmond et al., 2015; Li et al., 2020).

There are no simple solutions to mitigate the hazard of pesticides to humans and the environment, as the replacement of some molecules by others has reduced impacts in some sectors but has created other problems, such as the case of the replacement of DDT by organophosphates, and more recently, organophosphates by neonicotinoids (Davis 2014). A more integral assessment of the hazards, potential risks and trade-offs of pesticides is fundamental to solve one problem without the expense of exacerbating another.

4.3. From acute toxicity to an integral assessment of pesticides

Comparing the currently registered pesticides in Colombia to those of a more comprehensive (PAN) HHP list indicated that, although there has been a clear effort to limit hazardous products based on acute toxicity in the national market (e.g. integral set of assessments, reregistration process and transitioning to the GHS), there remain at least two major threads that require urgent action. The first thread is the current registered products that have active ingredients with high acute toxicity and/or are internationally regulated. Although these products could still be used under controlled application in terms of human and environmental protection, required conditions (e.g. equipment, knowledge, training, governance) are lacking in many regions in Colombia and other LMICs (Ecobichon, 2001; Karlsson, 2004). For example, Cárdenas et al. (2010) reported that, between 2002 and 2005, there were high levels of exposure of young adults and children to organophosphates and carbamates in many rural regions across Colombia. Varona et al. (2016) also described the poor economic conditions and reduced protection of agricultural labourers in a rice production region in Colombia, with higher intoxication levels of pesticides for those workers with lower literacy and limited access to health care. Additionally, Bastidas et al. (2013) found excessive pesticide residues in *Passiflora* fruits in several regions in Colombia, potentially reflecting high application rates of pesticides products in crops in which they were not registered for use. To address this thread, ICA in collaboration with the agrochemical industry, INS and INVIMA could survey the current application practices, exposure levels, and food residues of some of these more hazardous products to better evaluate their real current risk. Additionally, a national training and licensing program for pesticide handlers and applicators is required to allow a rational handling of pesticides and reduce personal and environmental exposure and risk. Finally, alternative management systems (e.g. integrated pest management, diversified agricultural production) or less harmful products for humans and the environment (e.g. Jepson et al., 2020) need to be identified and promoted to replace these products.

The second thread are the considerable numbers and amounts of highly hazardous pesticides sold in the country, which are not considered dangerous in the current official toxicity categorization but pose potential long-term risks to human health (McKinlay et al., 2008; Ross et al., 2012; Gonzáles-Alzaga et al., 2014; Mehrpour et al., 2014; Parrón et al., 2014; Yan et al., 2016) and the environment (Pekár, 2012; Pelosi et al., 2013; Jacobsen and Hjelmsø, 2014; Wood and Goulson, 2017). In fact, comparing these results to a similar study conducted with 2018 data on pesticide sales of the world's five largest agrochemical companies in 20 countries across the globe (UNEARTHED and Public Eye, 2020), Colombia seems to have a larger proportion of HHP than any of these countries. However, given the differences in the analysed years, additional data and further analysis are needed to confirm these preliminary findings. This suggests that the current categorization based primarily on acute toxicity for humans underestimates these less conspicuous but equally hazardous side effects for both humans and the environment (Mostafalou and Abdollahi, 2016; Sidhu et al., 2019). This thread could be tackled by using the ongoing adoption of the GHS to define or adapt a more comprehensive HHP list for Colombia, including more explicit and thorough assessments of the potential long-term risks of pesticide for human health and the environment. Another option is to adopt a list of the lower risk products to facilitate the selection and testing of pesticides products with similar (crop) protection properties but with limited hazards for human health and the environment (Jepson et al., 2020). Similarly, given the potentially serious consequences of HHP, regulation of some of these products (e.g. endocrine disrupting and neurotoxic chemicals) should move from the basis of a risk assessment (i.e. actual impact) to hazard identification (i.e. source of potential health effects), similar to the approach of the European Union (Bourguignon et al., 2016).

On the other hand, the current official registration processes requires information about the potential impact of pesticide products that often mix different active ingredients, adjuvants and other ingredients. However, general methodological and knowledge uncertainties regarding the toxicity of interacting chemical to which humans and the environment are indirectly exposed persist (Fluegge, 2017; Hernández et al., 2017, 2019), reinforcing the need for more integral approaches to reduce pesticide risk for humans and the environment (Möhring et al., 2020).

4.4. Methodological and research considerations

Analyses in this study require a closer look at three main methodological and research considerations. The first one is the use of the PAN HHP list. Although not endorsed by any country or main agricultural/health organization, this study illustrated the benefits of using more comprehensive lists such as the PAN. First, because there is no official alternative for a global and integrated HHP list and it would be politically very difficult to agree on one (FAO and WHO, 2019), the PAN list offers an integrated overview of pesticide hazard, particularly for countries such as Colombia with limited resources to conduct their own, broad and independent risk assessments. Second, although there are some differences in methodologies and classification of certain products between institutions (e.g. Tarazona et al., 2017), the PAN list is based on the work of different recognized organizations and international conventions including the WHO, US EPA, IARC, EU and several UN conventions, compiling and complementing more rigorous standards for integral comparisons of pesticide hazard. For example, Dawson et al. (2010) demonstrated that the WHO classification would be more accurate and less risky if it was combined with reported public health data on human toxicity (i.e. deliberate and unintentional exposure) and not only on animals (often rodents). Third, potential endocrine disrupting pesticides, which can represent a high risk for human health (Khan et al., 2020) and are not well regulated yet (Kassotis et al., 2020), are preemptively included in the PAN list (PAN, 2019). Last, the PAN list needs to be used as a dynamic supporting tool, accounting for the continuous updating of its sources. For instance, the latest version of the PAN was published early 2019 and could not include the recently published version of the WHO recommended classification (WHO, 2020).

The second consideration involves the potential limitations and lack of detail of the analysis because this study relied completely on the existing published official data on pesticide production and trade, which posed many limitations. First, published official data relies on the product registration, production and commercialization done by each company, without independent or complementary studies on legal and illegal pesticide use and markets. Second, although using active ingredients as the unit was not faultless (e.g. generalizing some information on acute toxicity for humans), it allowed reconciling dissimilar but complementary databases to obtain an overview of pesticide hazard in Colombia. Third, toxicity categories were extrapolated from products with multiple ingredients and specific concentrations to active ingredients that did not often specify any concentration, generating lack of clarity in the hazard results, and ignoring the potential impacts on toxicity of inert ingredients in product formulations. Although this study included the most frequent toxicity categories of each active ingredient to limit this lack of data, there is a need for official data that link pesticide ingredients and amount of pesticides produced and traded. Lastly, by using the latest reported national information, this study tried to include as much as possible the effects of the recent process of pesticide product revalidation, as well as the current patterns of pesticide production and trade. However, the latest version of these data available early 2020 were for the year 2016, missing recent data including a more accurate picture of the effect of the revalidation process on pesticide hazard. Despite this potential noise in the detailed analysis caused by limitations in data quality and availability, similar findings of pesticide hazard, production and/or trade have also been reported for other countries (e.g. Atreya et al., 2011; Hoi et al., 2013; Riggotto et al., 2014; García-Hernández et al., 2018; Donley, 2019; UNEARTHED and Public Eye, 2020; Zúñiga-Venegas et al.,).

Finally, the analysis of this study only focused on pesticide hazard based on the licensing, production and trade of products with high risks for human health and the environment. However, there remain major challenges in pesticide exposure and risk including: potential misuse and handling of pesticides related to the dependence of smallholder farmers on the (potentially biased) technical assistance of pesticide producers and/or sellers; lack of comprehensive and targeted information on the use and risks for farmers; poor capacity to control and monitor HHP in the field; poor capacity to monitor systematically the exposure and impact of pesticide use beyond direct intoxications; limited civil society organizations that could survey and demand safer pesticide use and residues in food and the environment; low public investment in alternative and diverse food systems that demand less synthetic pesticides; inadequate occupational health and safety conditions for those spraying pesticides; poor of access to the health system particularly for vulnerable populations; and poor investment in pesticide safety education among others (PAHO et al., 2006). To better contextualize and target more effectively these challenges, a better understanding on the dynamics of major drivers of pesticide registration and use (e.g. markets, agricultural and food systems, regulations) is essential (e.g. Braga et al., 2020).

4.5. Narrowing the information gap

Similar to other studies in LMICs (e.g. Bravo et al., 2014, UNEARTHED and Public Eye, 2020), the findings of this paper reinforced the claim that LMICs urgently need to close the information gap on pesticide hazard and exposure for humans and the environment (Dinham 2003; Kesavachandran et al., 2009; Schreinemachers and Tipraqsa 2012,(FAO and WHO, 2019; WHO and FAO, 2019)). Although general principles are needed (e.g. integral registration process, data transparency and availability, broader set of empowered actors, baselines and functional monitoring systems), the current conditions and ways forward would depend on each country. Specifically for Colombia, the results of this study identified three major steps to narrow this information gap, which should be part of a transparent and participatory process of knowledge creation and sharing to inform and empower the general public, policy makers and other relevant actors of the current exposure and potential pesticide risk, limiting the social production of ignorance (Kleinman and Suryanarayanan, 2013). The first step would be that ICA ensures data transparency by improving the structure, quality, availability, and interoperability of data on pesticide production and trade. Current available data have multiple spelling errors and were designed to register products, lacking: data cleaning, connectivity between tables, clear links between pesticides products and active ingredients, and standard international registry codes (i.e. CAS Registry Number). Based on this clean and better structured dataset, a second step would be that ICA, together with other relevant actors, redesign this database and broaden its scope from simply product registration to include explicit information on pesticide hazard, exposure, risk and impact. With relatively few modifications and data cleaning, these databases could also link data on production and trade at active ingredient level, including: number of products, amounts produced and traded, main chemical mixtures and concentrations without necessarily exposing confidential data of the chemical companies.

A subsequent major step would be to link this improved dataset into a consolidated, integrated and functional monitoring system similar to those already developed in other countries and regions (e.g. Bravo et al., 2011; Kudsk et al., 2018). Although many parts of such a system already exist, they are atomized in different organizations, reports and datasets weakening its fundamental monitoring and systematic properties. Additionally, the comparison with a more integral HHP list evidenced an even broader gap in the ecotoxicological hazard of pesticides produced and sold in Colombia. Therefore, a set of diverse and empowered actors including the civil society and environmental organizations should be part of the design, use and assessment of this monitoring system, moving towards an integrated environmental health governance (Briggs, 2008; Galvão et al., 2010; Schaëfer et al., 2019). For example, this redesigned set of distributed databases could be easily linked (e.g. based on active ingredient, crops and location) to the current data on pesticide residues in food of the National Food and Drug Surveillance Institute (INVIMA), monitoring of the pesticide poisoning and vector data of the INS, and monitoring of biodiversity, water and soil quality, or even linked to more integral anthropic impact analysis (e.g. Correa-Ayram et al., 2020). This monitoring system would also require a consolidated and urgently needed understanding and baseline on: i) amount and toxicity of imported pesticide products that are either transformed and sold in the local markets vs. imported; ii) current pesticide exposure in different regions and food production systems, including mayor challenges (e.g. knowledge, training, misuse, illegal pesticides) and drivers; iii) potential residues in main food chains, bioindicators (e.g. pollinators and aquatic fauna) and exposed agroecosystems (e.g. water and soils); iv) impact of pesticide use in high-risk rural communities (e.g. agricultural labourers and neighbouring communities), and key populations and communities of bioindicators; and v) institutional context including the effectiveness and gaps of current regulations, main involved and affected actors, and power distribution in decisions and legislation.

Narrowing the pesticide knowledge gap and this monitoring system would only be possible within an enabling institutional and governance context that do not prioritize short term economic profits based on strong lobbying, but also long-term risks, benefits and wellbeing of agricultural workers, rural communities, food consumers, biodiversity and the environment. Nevertheless, this is still a major bottleneck in pesticide regulation and the promotion of more sustainable agricultural and food systems across the globe (e.g. Sherwood and Paredes, 2014; Jansen, 2017; Trasande 2017; Nikol and Jansen, 2018), indicating that more fundamental changes are needed in the way we grow and value our food and agroecosystems (Meadows, 1999; Abson et al., 2017).

5. Conclusions

This study represents a basic but essential step to narrow the pesticide information gap in Colombia, and possibly in many similar LMICs. Colombia has been a regional player in the production and trade of agrochemical pesticides in the last decades. Although regulations to reduce the potential pesticide risk have been in place for more than a decade focusing mainly on acute toxicity, a considerable amount of hazardous pesticides products remain in the market. In fact, a quarter of the sales and the imports, and a third of the exports in 2016 were products with moderately to extremelyacute toxicity. Furthermore, while a large amount of the pesticides sold in 2016 were officially labeled as slightly toxic based on acute toxicity for humans, more than half of them are considered as highly hazardous chemicals for humans or the environment based on more integral categorizations. These findings suggest that Colombia needs to define or adapt a more comprehensive HHP list that includes acute and long term risks for both humans and the environment. The analysis of these results needs to consider the simplifications of using active ingredients without including concentrations or accounting for the mixing of different ingredients in the final products, or the focus on hazard without looking at pesticide exposure and risk. However, these simplifications were largely caused by lack of available data, which evidences once more the need for transparent information and monitoring systems (Antoniou and Robinson, 2017). In fact, this study supports previous calls to largely reduce the pesticide risk for humans and the environment in multiple fronts in Colombia and elsewhere (e.g. Möhring et al., 2020), including to bridge the knowledge gap of pesticide risk (Antoniou and Robinson, 2017) to put in place more inclusive pesticide monitoring and policy-making (Vélot, 2016; Topping et al., 2020), and to include preemptive integral assessment to limit both the short and long term pesticide risks (Dinham, 1993; Fluegge, 2017; Mesnage and Antoniou, 2018; Topping et al., 2020). Finally, this study also echoes the call to limit the use of HHP in agriculture (WHO and FAO, 2019), finding less harmful alternative products or even promoting and transitioning to food production systems that demand low or no agrochemical inputs while preserving the overall functioning of the agro-ecosystems (Nivia, 2001; Nicolopoulou-Stamati et al., 2016).

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

Acknowledgments

We would like to thank Mary Centrella and María Fernanda Díaz for their valuable comments on an early version of the manuscript. We would also acknowledge the helpful input of D. Jaramillo to better understand the pesticide product registration process. Finally, we thank the four anonymous reviewers for their constructive feedback.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112141.

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