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Food Additives and Contaminants - Part A

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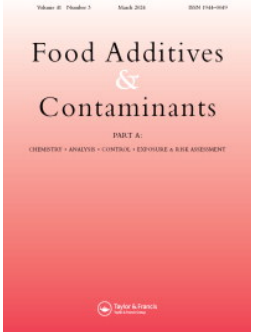

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RESEARCH ARTICLE

An account of the occurrence of residues from veterinary drugs and contaminants in animal-derived products: a case study on Brazilian supply chains

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ABSTRACT
Brazil plays an important role in ensuring its position on the international market by assuring high food safety standards for its products, and all products should meet the requirements for residues from veterinary drugs and contaminants in animal products. Statutory monitoring provides insights into the compliance of the Brazilian industry regarding these legal requirements. The objective of this study was to provide insight into the safety of Brazilian animal products by reporting the occurrence of residues from veterinary drugs and contaminants according to an analysis of an 11-year report published by the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA). Between 2010 and 2021, 166,647 samples from animal-derived products were analyzed in Brazil, and 624 of those samples were non-compliant (0.37%) exceeding maximum residue limits (>MRLs) or showed the presence of prohibited substances. The most common types of substances found in the non-compliant samples were heavy metals, parasiticides, and antimicrobials, accounting for 82% of all documents from the MAPA. Among Brazilian products, the challenge related to occurrence of substances varied across the food supply chain, with highest incidence rates observed in the fish chain, followed by eggs, milk, equids, sheep/goat, honey, bovine, swine, and broilers chains in decreasing order. Considering the type of substance, heavy metals were found to be more prevalent in fish products, mainly arsenic in wild fish. The prevalence of contaminants and heavy metals decreased, while that of veterinary drugs increased in Brazilian products from 2010 to 2021. From these results, it can be concluded that the number of accidental incidents including those associated with environmental contaminants decreased over the last decade, opposed to those involving human adversaries and deliberate illegal actions, such as the abuse of veterinary drugs, increased. Future monitoring plans need to take this paradigm shift into account.

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KEYWORDS
Heavy metal; food safety; antibiotics; agribusiness

Introduction

Globally, there has been an increasing food safety concern regarding the presence of residues from veterinary drugs and contaminants in animal food products. The major risk to consumers' health is the occurrence of toxicity, allergies, hypersensitivity reactions, mutagenic and carcinogenic effects, disruption of normal intestinal flora, and the development of antibiotic resistance from bacteria against antibiotic usage (Berends et al. 2001; Nisha 2008; Bayou and Haile 2017; Niang et al. 2017; Bacanlı and Başaran 2019; Lees et al. 2021; Hosain et al. 2021; Shao et al. 2021). To ensure the health of the population, the government regulatory authority requires guarantees on products across all segments of the food chain, from the primary sector to the consumer in each country, in addition to implementing monitoring systems for imported products, for instance, the European Rapid Alert System for Food and Feed (RASFF) and US import alerts developed by European countries and the USA. The best way to achieve this requirement is to follow the patterns recommended by the Codex Alimentarius Commission, and it is a requirement for many countries to participate in international markets

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and have their products accepted in other countries.

Brazil is one of the most predominant producers and exporters of animal products in the world; mainly chicken, beef, and pork meat. Yearly, the country has been increasing its production indexes, selling food products to more than 180 countries (Nonaka et al. 2012; Arisseto-Bragotto et al. 2017; Barros et al. 2021). The Ministry of Agriculture and Livestock (MAPA) in Brazil is responsible for ensuring food safety and overseeing the activities developed by industries through the inspection system. Therefore, the goals of the action from regulatory, control, monitoring, and checking the occurrence of any substance levels in animal products were set forth in the Brazilian National Plan for the Control of Residues and Contaminants in Animal Products (PNCRC; Brasil 1999).

The PNCRC programme aims to improve the productivity, quality, and safety of animal products in Brazil and ensures that the Brazilian population as well as international buyers have access to safe products in accordance with international rules following recommendations from the World Trade Organization (WTO) and other organizations (i.e. Food and Agriculture Organization-FAO, World Organization for Animal Health-WOAH, and World Health Organization-WHO). In case of non-compliance, e.g. violations of the Maximum Residues Limit (MRLs) or the presence of banned chemical compounds in Brazil, a sub-programme of investigation is initiated, and measures and corrective action are taken. The PNCRC monitoring system is applied to the following principal supply chains in Brazil: bovine, broilers, swine, eggs milk, fish, and honey. It also applies to other supply chains, such as sheep/goat, equids, rabbit, and ostrich, although Brazil is not a big exporter or producer of products from these chains.

The MAPA programme follows the guidelines established by the Codex Alimentarius Commission for sampling confidence reporting according to number of samples required to detect at least one non-compliant result with predefined probabilities in a population having a known non-compliance prevalence (Codex Alimentarius 2014). Therefore, a number of samples are pre-defined, collected in the industries, and subsequently sent to MAPA official laboratories for analysis of the residues of veterinary drugs and contaminants. For each matrix or chain, the PNCRC considers the monitoring of substances to ensure that they follow good practices in agrifood production and thus ensure that the products from these chains are safe. Each year, the programme publishes its results according to the number of samples collected and analysed and the number of non-compliant samples found.

The objective of this study is to examine the results of the monitoring programme report of PNCRC from the last eleven years (2010 to 2021) published by MAPA to identify the most prevalent substances showing non-compliant results and their temporal trends as well as differences between samples from bovine, broilers, eggs, equids, fish, honey, milk, sheep/goat and swine chains.

Materials and methods

Database

The study was conducted using data from the MAPA database at the PNCRC of Brazil for samples from bovine, broilers, eggs, equids, fish, honey, milk, sheep/goat, and swine chains that were tested between 2010 and 2021. The samples in the bovine chain were from live and slaughtered cattle, while in the chains from fish, equids, sheep/goat, and swine, samples were from slaughtered animals. Only the results from samples that violated the MRLs according to the parameters determined by the PNCRC in these chains were included for further evaluation. The non-compliance rates were determined in each chain and group of substances based on the occurrence of violation according to the number of samples collected and analyzed in each year.

In this study, the results from products with a low number of samples and relatively low frequency of analysis were excluded, such as rabbit in 2015 ($n = 2$), 2016 ($n = 2$), and 2019 ($n = 2$); and clam in 2019 ($n = 26$). Both products represented less than 0.02% of the total samples collected and were analysed for heavy metals, and there was no occurrence of non-compliant samples. The data from the fish chain included all kinds of fish species and their origins (i.e. farmed fish, wild fish, and farmed shrimp).

Data analysis

The significance of the effects of the factors that may affect the non-compliance incidence rate, i.e. type of chains, groups of substances, and time was determined by F tests followed by multiple pairwise comparisons using Tukey and LSD means tests. A significance level of $p < 0.05$ was applied throughout the study. All statistical analyses were performed using the IBM SPSS® 20.0 statistical package.

For trend analysis of the incidence rates of non-compliant samples during the period analysed, regression analyses were conducted using Joinpoint statistical software version 4.9.0.0. The time trends of the adjusted non-compliancy data, in general, for veterinary drugs, contaminants, and heavy metals, were calculated by employing Joinpoint regression models (Kim et al. 2009; Santos et al. 2020). The Joinpoint regression was based on the calculation of annual percentage changes (APCs), calculated for each segment, and average annual percentage changes (AAPCs) for the entire period, with their respective 95% confidence intervals (95% CI). For this analysis, each junction point indicated a statistically significant change in the slope tested using the Monte Carlo permutation test. Trends were considered statistically significant when the APC if $p < 0.05$. The results were interpreted as follows: positive and significant APCs/AAPCs were considered increasing trends, and negative and significant APCs/AAPCs were considered decreasing trends; on the other hand, when there was no significance, the trend was considered stable.

Results and discussion

The results of the PNCRC in different animal product chains from 2010 to 2021 are presented in Table 1. Samples by chain were analysed for residues from veterinary drugs and contaminants, and they were classified as non-compliant samples when the level of these substances was over the MRLs. Following the Codex Alimentarius (2021) recommendation for methods of analysis and sampling, these samples were collected from 3,063 industries under the Federal Inspection Service (SIF). In 2023, there was a total of 879 factories in the meat chain, 1,213 in the milk chain, 241 in the honey chain, 510 in the egg chain, and 270 in the fish chain under the SIF service. They represent respectively 24.9%, 38.0%, 7.5%, 15.7%, and 8.5% rates considering a total number of regulated industries (Brasil 2023). As a result, these industries are responsible for most animal-derived products produced in Brazil, and they concern slaughtered animals in the bovine, broilers, and swine chains, which are responsible for 77.6%, 91.5%, and 85.5% of the total carcass weight on the market, respectively, as well as 91.3% of the total volume of milk produced in the milk chain (IBGE, 2021). Thus, the results used in this study represent most of the products that are consumed by Brazilians and exported to other countries.

In general, the number of samples collected and analysed on PNCRC in Brazil for the 11 years in each chain was according to their participation in Brazilian agribusiness. Three major chains accounted for 81.2% of the samples collected and analysed: bovine (33.9%), broilers (27.8%), and swine (19.6%). These are also the food chains for which Brazil is a global leader in production and export. The other smaller group of samples included samples from chains of milk (6.2%), fishes (6.1%), eggs (2.6%), equids (2.2%), honey (1.5%), sheep/goat (0.1%), and ostrich (0.1%). The PNCRC programme tests for substances and contaminants belong to the group of anabolic substances, dioxins, chemical compounds (including pyrethroids, organophosphates, and chlorinated pesticides), beta-agonists, antimicrobials, parasiticides, coccidiostats, anti-inflammatory compounds, sedatives, heavy metals, and mycotoxins. Sheep and goat products were the only chain that had no samples analysed for antimicrobials. Generally, this type of substance was tested for in each group based on the risk of occurrence, considering the characteristics of the production system and the risk of occurrence in the primary production. The model of sampling used in the PNCRC plan is based on

Table 1. Results for animal-derived samples tested for substances against the Maximum Residues Limit in Brazil from 2010 to 2021[a].

	Number of samples collected and analyzed per animal product chain											
Substances tested	Bovine	Broiler	Eggs	Equids	Fish	Honey	Milk	Ostrich	Sheep/Goat	Swine	Total	NC(#)	NCP (%)
Anabolic substances	15,312	474	–	461	544	–	–	–	–	1,665	18,456	17	0.09[a]
Anti-inflammatory compounds	1,570	–	–	253	–	–	130	–	–	621	2,574	4	0.16[a]
Antimicrobials	15,195	28,519	2,641	930	5,093	1,403	4,147	75	–	14,314	72,317	147	0.20[a]
Beta-agonists	6,784	748	–	193	–	–	–	–	–	2,172	9,897	20	0.20[a]
Chemical compounds	2,508	936	363	347	831	739	1,168	–	–	974	7,866	10	0.13[a]
Coccidiostasts	719	6,966	621	–	–	–	–	–	–	190	10,073	53	0.63[a]
Dioxins	232	2,028	641	–	712	–	281	–	–	966	4,860	6	0.12[a]
Heavy metals	4,490	4,130		615	2,955	317	646	88	149	3,192	16,582	247	1.49[a]
Mycotoxins	34	327	–	14	–	–	1,042	–	–	347	1,764	1	0.06[a]
Parasiticides	8,586	2,143	–	666	46	–	2,896	–	17	7,410	21,764	119	0.55[a]
Sedatives	1,017	–	–	238	–	–	–	–	–	816	2,071	0	–
Total	56,447	46,271	4,2664	3,717	10,181	2,459	10,310	163	166	32,667	166,647	624	–
NC (#)	157	64	60	22	188	8	51	0	1	73	624	–	–
Average NCP (%)	0.29[b]	0.12[b]	0.73[ab]	0.51[ab]	1.05[a]	0.27[ab]	0.52[ab]	–	0.39[ab]	0.18[b]	–	–	0.37

[a]Tukey Test ($p < 0.05$), (n) Number; (NC) number of non-compliant samples, (NCP) Percentage of non-compliant samples.

Hypergeometric and Binomial Distribution Models (Barros et al. 2021). This model is adequate for a population over 5000 units available to be evaluated, such as thousands of animals slaughtered or units of products obtained in each Brazilian chain during a year of production. Thus, the number of samples collected on the PNCRC plan is robust with a high coefficient of confidence (95%) to detect a violation of parameters from MRLs in the population of samples analysed at least with 1% of prevalence following the CAC/GL 71-2009 - Guidelines for the Design and Implementation of National Regulatory Food Safety Assurance Programmes Associated with the Use of Veterinary Drugs in Food Producing Animals recommended by Codex Alimentarius Commission.

The main groups of substances and contaminants tested were for antimicrobials (43.4%), parasiticides (13.1%), anabolic substances (11.1%), and heavy metals (10.0%). The high number of samples collected and analysed for the occurrence of residues from antimicrobial substances exhibits the concern on their use in husbandry practices. Antimicrobial residues, mainly antibiotics, in foods, have become a global problem, and the monitoring of these substances helps to prevent their misuse. Antibiotics have great importance in livestock and are used to treat infectious diseases caused by bacteria as well as growth promoters to preserve the performance of animals, especially in intensive animal production systems. However, this substance may pose a threat to human health due to an increase in antibiotic resistance from bacteria and declining drug efficacy, in addition to allergic reactions and disrupted intestinal flora (Bayou and Haile 2017; Novaes et al. 2017; Shao et al. 2021). Reports by MAPA indicate that during the period from 2010 to 2021, approximately 166,647 samples were collected and analysed, and 624 (0.37%) non-compliant samples were detected. Only in the ostrich chain, no non-compliant samples were found when antimicrobials and heavy metals were screened.

The greatest incidence rate of non-compliant samples was found in the fish chain, in decreasing order followed by eggs, milk, equids, sheep/goat, honey, bovine, swine, and broiler chains ($p = 0.002$) (Table 1). The results from PNCRC-MAPA showed a lower number of samples violating MRLs across different product chains, except for the fish chain, where the incidence rate of non-compliant samples exceeded 1%. In each food chain, the proportion of non-compliant samples was different and smaller than the results reported by EPSA for the National Residue Control Programme by Fink-Gremmels (2014) between 2005 and 2010 for bovine (0.90%), sheep and goat (0.92%), pig (0.30%) and chicken (0.23%). Ensuring product safety is a challenge for every country, and the best outcome would be that there is no occurrence of non-compliant samples. Nevertheless, there are still some flaws in system production to be considered, which reinforces the importance of a monitoring system and the adoption of measures designed to reinforce the good agricultural practices in each chain.

In Brazil, the percentage of non-compliant samples with veterinary drugs and contaminants detected in the PNCRC-MAPA remained steady, and there was no significant difference among years ($p = 0.448$). All three major animal chains (i.e. bovine, broiler, and swine) have shown stable prevalence across the years, with a lower proportion of non-compliant samples. Despite no significant statistical interaction between chains and years ($p = 0.969$), some chains show a higher numeric incidence rate of non-compliant samples depending on the year analysed, such as fish, eggs, equids, and sheep/goat chains (Figure 1). Thus, in some chains, these rates are constant, whereas in others, they will depend on substances types found on different groups of veterinary drugs or contaminants. Brazilian animal products have been keeping the average incidence rate of non-compliant samples under 1%, with a range of 0.19 to 0.76%, and regression analysis showed a tendency for stability from 2010 to 2021 ($p = 0.501$).

The stability of the incidence rate of non-compliant samples on supply chains represents the correct use of good husbandry practices by the farmers, as well as the effectiveness of the control measures adopted in Brazil by PNCRC-MAPA aiming to ensure the food safety of animal products for consumers with a low level of violations on the different products for these compounds (Spisso et al. 2009; Nonaka et al. 2012; Alkmim Filho et al. 2014a, 2014b; Novaes et al. 2017; Bortolotte et al. 2021; Silva et al. 2021).

The results indicate that the main issue with non-compliant samples was contamination with heavy metals (Figure 2). Between 2010 and 2021, there was a constant occurrence of this issue, leading to an incidence rate of 39.6% of total non-compliant samples (247 of 624), which was nearly 80% of the source for non-compliant samples depending on the year studied. Every year, the incidence rate of non-compliant samples of antimicrobials was between 0.03% and 0.3%, accounting for 24.4% of the total non-compliant samples (152 of 624). The incidence rate of non-compliant samples of parasiticides was 0.1% and 1.0%, accounting for 18.8% of the total non-

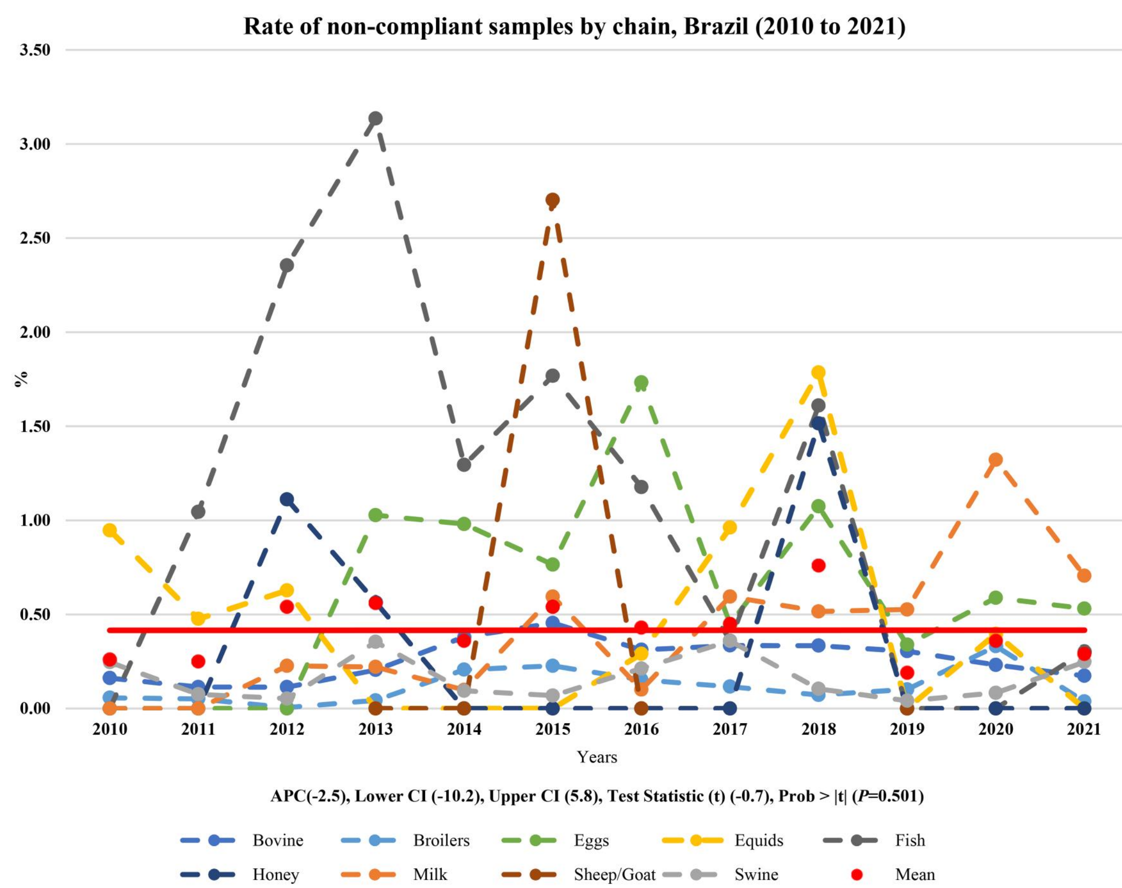


Figure 1. Proportion of non-compliant samples in Brazil from 2010 to 2021 for various animal-based supply chains.

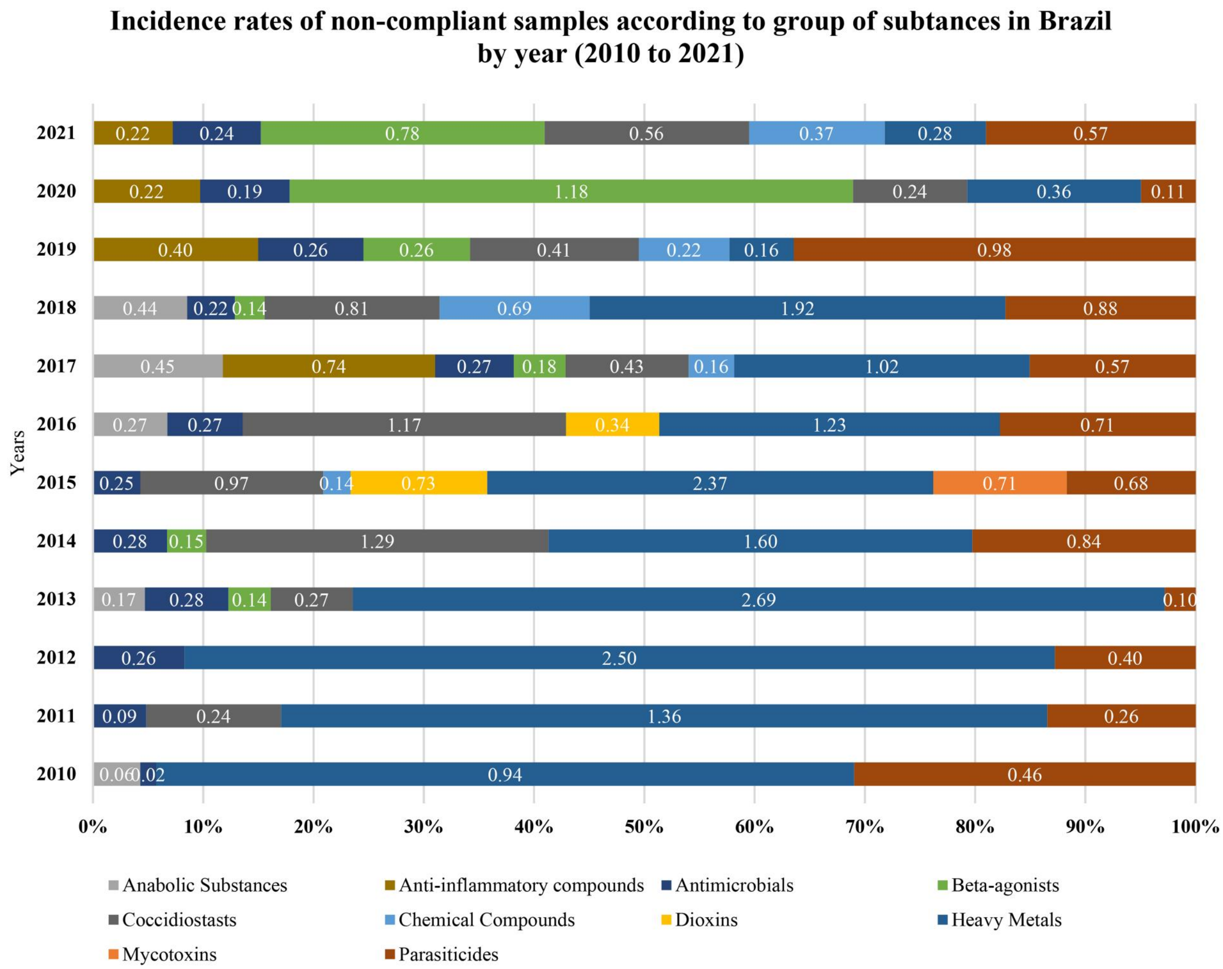


Figure 2. Incidence rates of non-compliant samples (%) of the principal groups of substances identified in animal-derived samples in Brazil by year (2010–2021).

compliant samples (117 of 624). In contrast, coccidiostats, beta-agonists, anti-inflammatory compounds, chemical compounds, and anabolic substances were variable throughout the period, and they were not detected every year for the samples analysed.

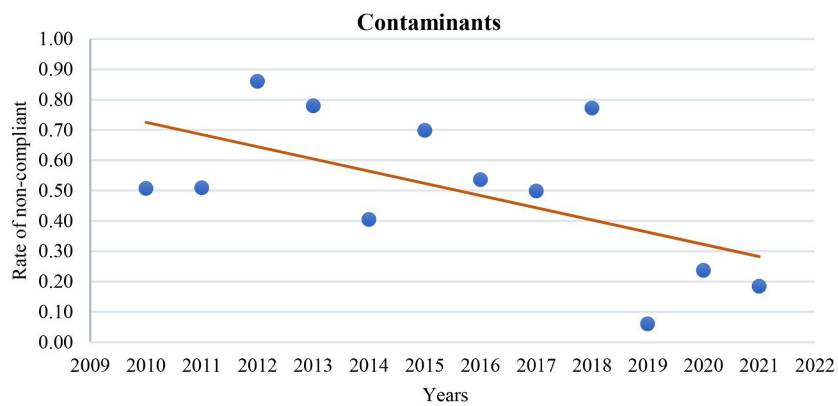
Only the samples from 2015 showed a problem with mycotoxins. The majority of mycotoxin concerns in public health are related to ochratoxin A, fumonisins, and aflatoxin B_1, and as a result, the contamination has been monitored mainly as a potentially higher-risk occurrence in foods obtained from cereal sources (direct source) or through animal products (indirect source) (Bryden 2007; Adegbeye et al. 2020). In humans, mycotoxins are linked to carcinogenic, mutagenic, and teratogenic effects, as well as other health problems, such as immunosuppression and reduced growth and development (Reddy et al. 2010).

Other contaminants of greater concern are polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDFs) or generally indicated how dioxins, and in 2015 and 2016, this compound was detected in Brazilian products (Figure 2). Brazil started in 2012 with routine testing for dioxin in food products, and ever since the number of samples collected and analysed has been increasing. These compounds are derived from industrial processes, solid waste incineration, and the production of herbicides, and because of their carcinogenic, immunomodulatory, and teratogenic effects, they present a health risk through contamination of products (Roeder et al. 1998). Humans are exposed to these substances directly through atmospheric emissions, contamination in plants and soil, as well as through the products of animals during husbandry when the animals are kept on contaminated land or fed contaminated food.

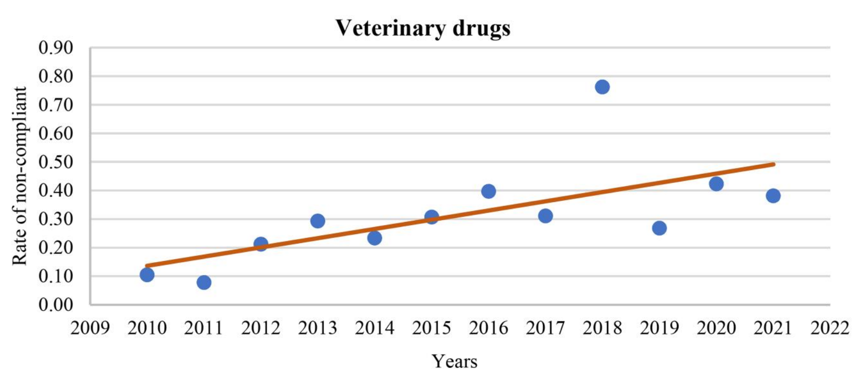
Nevertheless, while there was an increase of 11.3% per year for veterinary drugs ($p = 0.011$), the non-compliant sample rate for contaminants decreased by 12% annually ($p = 0.031$) as shown in Figure 3.

Some authors claim that antibiotic use is likely to increase until 2030 in developing countries due to animal protein consumption and intensive farming practices (Hosain et al. 2021). These concerns should also extend to substances associated with veterinary drugs according to the PNCRC results in Brazil from 2010 to 2021, highlighting the importance of using good practices in agri-food production to prevent health risks associated with the increasing occurrence of harmful substances in food products. Brazil has been adopted food safety policies to ensure the quality of its products and has an organization system based on the Codex Alimentarius guidelines through MAPA and the Ministry of Health that promote a control on food supply monitoring from primary production to food services with different implemented national programmes and reference laboratories that have given support to these Brazilian agencies, besides that is made in PNCRC programme (Camino Feltes et al. 2017). Thus, these actions enhance the use of good agriculture practices in every chain aiming to expand markets and consolidate its position as one of the biggest animal-origin food producer country in the world, once the challenges in the livestock tend to increase mainly in an intensive production where food should be sustainable, available and safety to supply a global demand for food that is progressively increasing.

Among the chains with heavy metal contamination, fish had the highest incidence rates of non-compliant samples (5.9%, 173 of 2,955), followed by equids (2.3%, 14 of 615), and sheep/goat



APC(-12.0), Lower CI (-21.4), Upper CI (-1.4), Test Statistic (t) (-2.5), Prob > |t| (*P*=0.031)



APC(11.3), Lower CI (3.1), Upper CI (20.2), Test Statistic (t) (3.1), Prob > |t| (*P*=0.011)

Figure 3. The regression analysis of non-compliant animal-derived samples for contaminants and veterinary drugs in Brazil from 2010–2021.

(0.7%, 1 of 149) chains (Figure 4). There were chemical compounds found in samples of honey, milk, and fish chains; and residues of dioxins were found in samples of broilers, eggs, and swine. Among the contaminants, mycotoxin (0.01%, 1 of 11,042) was the least frequent and only found in the milk chain.

The presence of contaminants such as heavy metals, mycotoxins, dioxin, and pesticides in animal products could be influenced by the source of contamination such as plants, soil, or feedstuff in the primary sector. These compounds can be found spreading in the environment and indirectly become harmful to human health through the consumption of meat, eggs, honey, and milk with the presence of contaminants over the MRLs.

Chemical compounds generally belong to the pesticide group and have been used in agriculture or husbandry in the past. In most countries, however, they were banned because these compounds offered a direct health hazard to consumers through contact with food. Animal products are usually contaminated with these compounds due to their characteristics, such as lipid solubility and bioaccumulation in animal tissues. In people exposed to these compounds, adverse effects are reported, ranging from acute toxic effects and skin and eye irritation to central neurotoxic effects, cardiovascular toxicity, damaged reproductive systems, endocrine alterations, genotoxicity, and immunotoxicity (Pathak et al. 2022).

Among the non-compliant samples, a higher prevalence of parasiticides was found in the bovine chain (1.1%, 93 of 8,586) and in the milk chain (2.3%, 3 of 130) (Figure 4). Antimicrobial residues were the most common cause of non-compliant samples in the honey chain (0.4%, 6 of 1,403) and came in second place in the eggs chain (1.8%, 41 out of 2,333). For coccidiostat, the broilers chain had a prevalence incidence rate of 0.4% (29 of 6,966) whereas in the eggs chain it was 1.8% (17 of 929).

Most substances found in non-compliant samples were antimicrobials, coccidiostats, and parasiticides permitted for use in food animals. Most antibiotics are used in broilers and swine chains as growth promoters, while parasiticides are commonly used in bovine, milk, and equids chains to

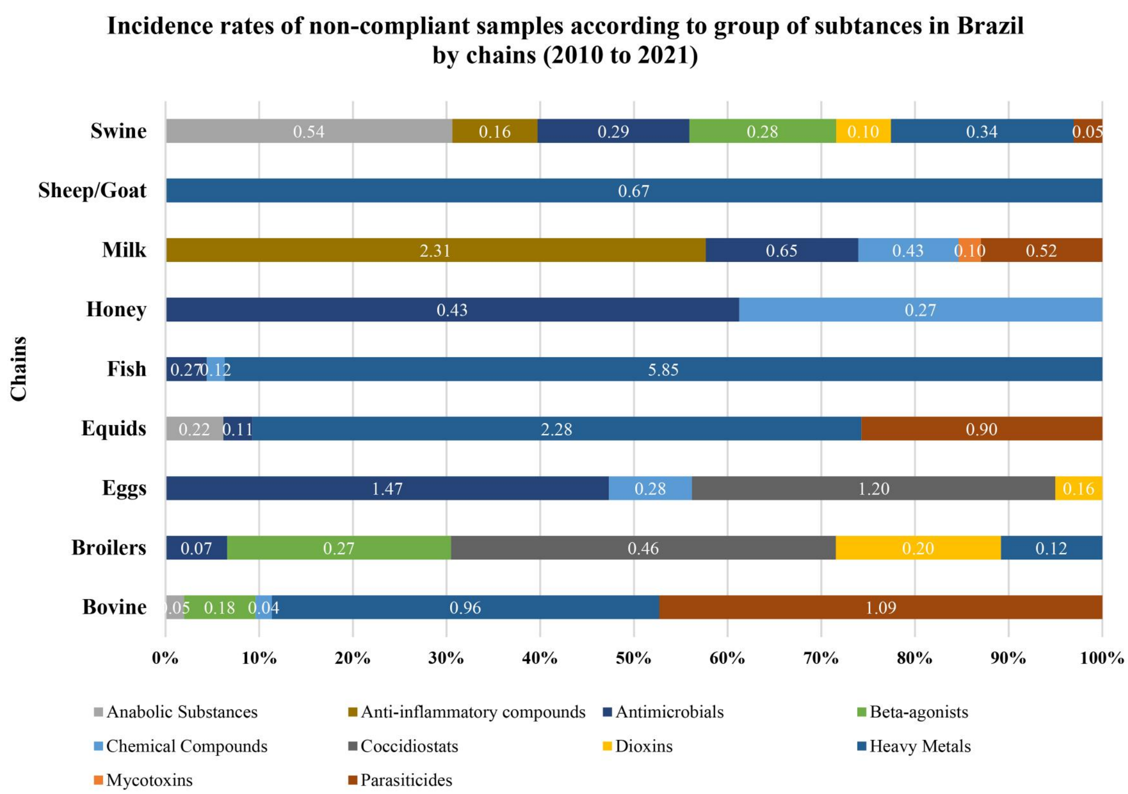


Figure 4. Incidence rates of non-compliant samples (%) of the principal groups of substances identified in animal-derived samples in Brazil by chains (2010–2021).

prevent the negative impact of parasites on animal performance. In addition to other veterinary drugs, beta-agonists are used in swine production to improve animal performance. Anti-inflammatory drugs are also commonly prescribed and used in animals as veterinary drugs. The occurrence of non-compliant samples from these compounds is most often associated with the lack of a correct withdrawal period after veterinary drugs administration during husbandry practice, besides the incorrect use such as improper route of administration or use of dose over the therapeutic limit (Olejnik and Szprengier-Juszkiewicz 2007; Novaes et al. 2017; Silva et al. 2021).

Despite anabolic substances being banned in Brazil in livestock, they were detected in the bovine (0.06%, 7 of 15,312) and equids (0.22%, 1 of 461) chains. The incidence of illegal substances is related to the fact that these substances are being introduced to the black market and are being intentionally used to improve animal performance; therefore, this group has greater importance regarding monitoring at the PNCRC. Brazil has not allowed the use of anabolic substances to accelerate growth in animals for slaughter or increase meat production since 1991 (Spisso et al. 2009).

Figure 5 shows the prevalence incidence rate of non-compliant samples related to the presence of heavy metals in Brazilian products by chain. The fish chain was divided into farmed shrimp, farmed fish, and wild fish. There was a greater number of samples contaminated with heavy metals in wild fish (172 samples), which justified the growing incidence rate of non-compliant samples in the fish chain. Non-compliant samples in farmed shrimp with heavy metals were only observed in 2018 (2.4%, 1 of 41). The equids chain also had a higher number of non-compliant samples with heavy metal contamination, and it had an incidence rate between 3.2% and 7.7%, while the bovine chain it was between 0.2% and 1.5%. There were fewer incidents of this risk in non-compliant samples in the broilers (0.3% to 0.4%), swine (0.3% to 1.5%), and sheep/goat chains (2.7% only one sample in 2015).

A total of 10,181 samples were collected and analysed at the PNCRC between 2010 and 2021, out of which 2,055 were from wild fish, 5,592 were from farmed fish, and 2,534 were from farmed shrimp. Based on the differences individually determined by source and type of fish, wild fish had an incidence rate of a non-compliant sample of 11.8% for heavy metals (172 out of 1,461), farmed shrimp had 0.2% for heavy metals (01 out of 562), while farmed fish did not have any non-compliant samples for heavy metal. Therefore, the problem with heavy metals in the fish chain is related to the source of these products, with 99.4% of contaminations being from wild fish.

Contaminants in animal products constituted 42.3% of the total non-compliant samples (264 out of 624), and heavy metals (arsenic, cadmium, mercury, and lead) made up the majority (92.9%) of these samples (Table 2). However, considering the occurrence of heavy metals in each chain, approximately 70% of contamination was related to arsenic, and 71% was related to fish, as reported previously, with 99% of issues related to fish. A total of 93.1% (161 out of 173) of the non-compliant samples in fish were wild fish contaminated with arsenic. This situation shows that the problem of contamination in the fish chain has a relationship to the source, i.e. wild fish captured from nature, or the environment (being less controlled) have a higher risk of occurrence over the limits of legislation than farmed fish, and the most frequently detected heavy metal was arsenic.

Arsenic has been considered an element of more concern in aquaculture, especially for freshwater fish producers, because anthropogenic processes and bioaccumulation can reach humans and cause toxic effects (Kumari et al. 2017). And, the most common source of arsenic in fish products such as wild shrimp compare to farmed shrimp, is the organic form (Matos et al. 2022). For the PNCRC samples in Brazil analysed between 2010 to 2021, the arsenic levels were interpreted as total arsenic without differentiation of source (organic or inorganic).

In addition to the large amount of arsenic found in non-compliant samples from the fish chain, arsenic was found in samples from the broilers and equids chains and represented 80.0% and 42.9% of the source of heavy metals, respectively. It is crucial to prioritize public health

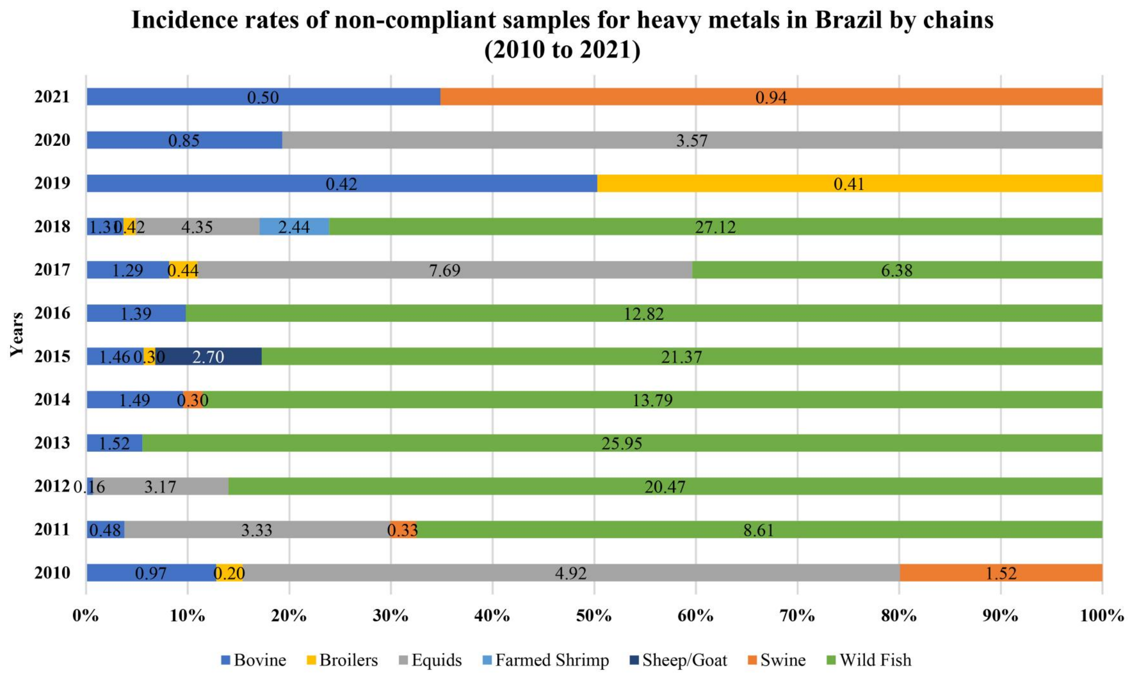


Figure 5. Incidence rates of non-compliant samples (%) for heavy metals identified in animal-derived samples in Brazil by chains (2010–2021).

Table 2. Contaminants identified in non-compliant samples in Brazil from 2010 to 2021.

Contaminant	Chain	Compound	n	%	Means	Minimum	Maximum	MRL*
Chemical compounds	Bovine	Chlorpyrifos ethyl (fat)	1	100.00	50.47	–	–	10
	Eggs	Diflubenzuron	1	100.00	137.56	–	–	50
	Fish (Farmed)	Diflubenzuron	1	100.00	38.08	–	–	10
	Honey	Acephate	2	100.00	24.05	22.89	25.2	20
	Milk	Chlorpyrifos ethyl	4	80.00	60.50	30.57	102.60	20
		Ethion	1	20.00	25.17	–	–	10
Dioxins	Broilers	PCDD/PCDF (fat)	4	100.00	2.84	2.14	3.53	1.75**
	Eggs	PCDD/PCDF	1	100.00	4.49	–	–	2.5**
	Swine	PCDD/PCDF (fat)	1	100.00	1.52			1**
Heavy metals	Bovine	Cadmium (kidney)	42	97.67	2150.89	1063.00	>9999.99	1000
		Lead (kidney)	1	2.33	521.40	–	–	500
	Broiler	Arsenic (liver)	4	80.00	1387.67	1138.75	1552.00	1000
		Cadmium (liver)	1	20.00	1503.00	–	–	1000
	Equids	Arsenic (muscle)	6	42.86	29.82	11	80.87	10
		Cadmium (muscle)	8	57.14	425.57	260.59	1201.25	200
	Fish	Arsenic (farmed shrimp)	1	93.64	2137.20	–	–	1000
		Arsenic (wild fish)	161		2470.69	1014.00	>9999.99	1000
		Cadmium (wild fish)	3	1.73	165.06	151.56	187.63	100
		Lead (wild fish)	2	1.16	346.68	345.85	347.50	300
		Mercury (wild fish)	6	3.47	2613.75	1330.00	8160.00	1000
	Sheep and Goat	Cadmium (kidney)	1	100.00	1200	–	–	1000
	Swine	Cadmium (kidney)	11	100.00	1676.42	1039	2746	1000
Mycotoxins	Milk	Aflatoxin M1	1	100.00	0.82	–	–	0.5

*Maximum Residues Limit (µg/kg); ** WHO-TEQ (pg/g); (n) number.

awareness of the dangers of arsenic in foods due to its inorganic form being classified as carcinogenic, while its organic form (arsenobetaine) is less toxic and it was the most abundant compound found in fish (Ciminelli et al. 2017; Taylor et al. 2017). On the other hand, in other chains, the problem associated with arsenic may be caused by contamination of drinking water or feed used in husbandry (Ghosh et al. 2012). Additionally, this concern extended to the presence of mercury (in fish chains) and lead (in fish and bovine chains), both of which are harmful to human health (Table 2).

Cadmium was the common heavy metal found in the non-compliant samples from the bovine, swine, sheep/goat, and equids chains (Table 2). Cadmium is widely distributed in the environment due to its use in various industries also be found in commercial fertilizers containing phosphate, usually from phosphate rock and used in soil. It is absorbed by plants through bioaccumulation in food and animal products when exposed plants are used to feed animals. Animal products could have been contaminated by this heavy metal when discharges of industrial effluents and phosphate fertilizers from agricultural practices, apart from the use of arsenical compounds for feeding animals. The prevalence of grazing systems for bovine husbandry in Brazil may make cattle more susceptible to this source of contamination in soil or feedstuff, likely resulting in a greater number of non-compliant samples related to this metal in samples from a bovine chain. Nevertheless, it is necessary to implement measures to reduce the contamination and occurrence of these compounds in every supply chain, due to the risk to the consumers' health.

However, the number of occurrences of heavy metal in Brazilian products has been decreasing significantly ($p = 0.031$) at a rate of 15.8% per year from 2010 to 2021 (Figure 6). The main reason could be attributed to the prohibition of using arsenicals as growth promoters, such as in broilers and swine chains (Alkmim Filho et al. 2014b), and the adoption of better agricultural practices in Brazil in the last years that have led to lower heavy metal levels (including arsenic, cadmium, and lead) in soil and products from crops, in compliance with Codex Alimentarius recommendations (Corguinha et al. 2015).

Non-compliant samples from the swine, broilers, and eggs chains showed the presence of polychlorinated dibenzo-para-dioxins (PCDDs) and dibenzofurans (PCDFs). These compounds belong to the dioxin group and are generally associated with contamination of the source of feed for animals (Weber et al. 2018). In general, there are no safety limits for these compounds in foods, and their MRLs are calculated based on the analytical methods capable of detecting occurrence in each type of sample.

Chemical compounds were found in samples from the bovine, eggs, fish; honey, and milk chains. Chlorpyrifos ethyl was detected in the bovine and milk chains; diflubenzuron was detected in the fish and eggs chains; acephate was detected in the honey chain, and ethion was detected in the milk chain. Acephate and chlorpyrifos ethyl compounds belong to the organophosphate group and are used on agricultural food and feed crops. They are among the top 10 most commonly detected pesticides (above 200) in samples collected between 2013 and 2015 by the Brazilian Programme on Pesticide Residue Analysis in Food (Arisseto-Bragotto et al. (2017). The occurrence of acephate may be related to contamination in nectar from the widespread use of this product in crops where bees are used for pollination purposes. Chlorpyrifos and ethion are used to control ectoparasites such as ticks in dairy farms and cattle husbandry, and thus could also remain when improper withdrawal of product or misuse occurs in lactating cows (Nascimento et al. 2021). Consumer exposure to these substances over the MRLs has been shown to have neurotoxic effects, chromosomal alterations, lesions of the liver and kidney, allergies,

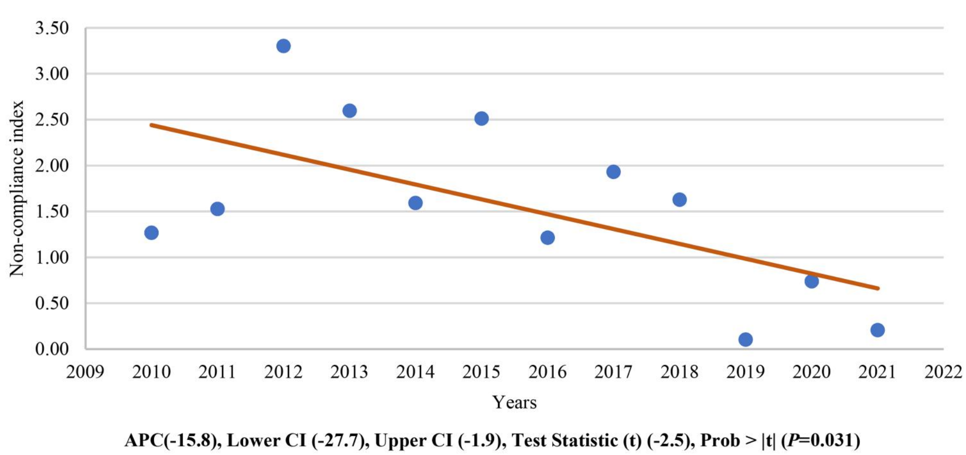


Figure 6. Regression analysis of non-compliant sample violations with heavy metals in Brazil from 2010 to 2021.

asthma, Parkinson's disease, and some types of cancer (Marques and da Silva 2021).

Aflatoxin M_1 was the mycotoxin identified in non-compliant samples from the milk chain (Table 2). It is the principal metabolite derived from aflatoxin B_1, which is transferred from contaminated feed to food animals after being secreted into milk by lactating cows (McEvoy 2002). In Brazil, the climatic condition is a reason for concern for the development of mycotoxins in animal feed (such as corn) during storage, handling, and harvesting as it can promote the growth of fungi and increase the incidence of mycotoxins (Arisseto-Bragotto et al. 2017). However, another important source of mycotoxins is grass or forage contamination in grazing systems, where cows can transfer mycotoxins to humans through their milk (Adegbeye et al. 2020).

Ivermectin was the most common compound found in non-compliant samples for parasiticides in the bovine, swine, milk and equid chains, and doramectin and abamectin was also found in the equids, bovine, and milk chains (Table 3). Compounds from the avermectin group were predominant in non-compliant samples in the parasiticides group from bovine, milk, equids and swine chains; and accounted for 94.1% (112 of 119). In husbandry practices, they are used to prevent and treat the occurrence of endoparasites and ectoparasites. Ivermectin was the principal substance found in the avermectin group (76.8%). The presence of these substances was also reported by Novaes et al. (2017), who analyzed 961 milk samples and found that 295 (30.7%) of the sample had some level of them present. Macedo et al. (2015) also detected ivermectin residues in 89.5% of butter samples. Furthermore, the Brazilian Programme for Residue Analysis of Veterinary Drugs (PAMVET) reported that ivermectin residues was the most prevalent parasiticide found in milk samples, and the level detected was below the MRLs, with 41.3% of UHT milk and 52.2% of milk powder samples in 2009 testing positive for this compound (Arisseto-Bragotto et al. 2017). The second most common parasiticide found in the milk chain was albendazole (Table 3), which belongs to the benzimidazole class of anthelmintics and is authorized for use in ruminants since it provides a sufficient withdrawal period to avoid its occurrence in milk (Daeseleire et al. 2017).

The compound fipronil was found in non-compliant samples in the milk and bovine chains on PNCRC. Although this compound has been analysed as a parasiticide for bovine chain, it has also been included in a group of chemical compounds for milk, and its concern for public health is because there is a highly toxic risk for humans (Marques and da Silva 2021). Thus, it is likely that fipronil residues were found in both chains (milk and bovine) because of inadequate application of commercial products with this compound by farmers in lactating dairy cows or cattle to promote tick control (Nascimento et al. 2021).

In the broilers and eggs chains, lasalocid, nicarbazin, and semduramicin were the main coccidiostat substances found in non-compliant samples, followed by salinomycin and trimethoprim (Table 3). In addition, the occurrence of robenidine was detected in non-compliant samples of the eggs chain. There have been reports of these compounds being found in other countries, such as Korea by Kang et al. (2015), who reported the presence of nicarbazin in eggs. In general, these substances can be used as growth promoters in broilers, but they are contraindicated in laying hens due to its occurrence in eggs (McEvoy 2002; Dowling et al. 2005; Olejnik and Szprengier-Juszkiewicz 2007).

Ractopamine is a beta-agonist and was found in non-compliant samples from swine, bovine, and broiler chains (Table 3). Ractopamine is a substance commonly used as a feed additive authorized by MAPA in Brazil. While it is used as an energy repartitioning agent for increasing muscle mass and decreasing fat deposition, promoting improvement in animal feed conversion and better daily weight gain average in swine, many countries have banned its use because of its unknown toxicological and pharmacological effects (Aroeira et al. 2019).

Non-steroidal anti-inflammatory products were found in four non-compliant samples from swine and milk chains, with one sample containing meloxicam, and two samples containing diclofenac. Diclofenac is an auxiliary medication used in

Table 3. The group of veterinary drugs substances detected in non-compliant animal-derived samples in Brazil from 2010 to 2021.

Substance class	Chain	Compound	n	%	Mean	Minimum	Maximum	MRL*
Anabolic substance	Bovine	Zeranol	7	100.00	11.41	2.50	40.31	2
	Equids	Zeranol	1	100.00	107.2	–	–	2
	Swine	Beta boldenone	9	100.00	5.31	1.40	19.5	1
Anti-inflammatory compounds	Milk	Diclofenac	2	66.67	0.16	0.15	0.17	0.1
		Meloxican	1	33.33	20.90	–	–	15
	Swine	Diclofenac	1	100.00	7.38	–	–	5
Beta agonist	Bovine	Ractopamine (muscle)	9	100.00	4.32	0.30	33.87	0.1
		Ractopamine (urine)	3		9.28	1.26	24.00	1
	Broilers	Ractopamine (liver)	2	100.00	3.57	0.56	6.57	0.17
	Swine	Ractopamine (liver)	4		54.63	43.30	77.43	40
		Ractopamine (muscle)	1		92.7	–	–	40
		Ractopamine (urine)	1		1.47	–	–	1
Coccidiostats	Broilers	Lasalocide	3	9.38	85.50	31.98	121.00	20
		Nicarbazin	27	84.38	450.29	253.76	867.67	200
		Senduramycin	1	3.13	71.93	–	–	50
		Trimethoprim	1	3.13	107.35	–	–	50
	Eggs	Lasalocide	1	4.76	15.27	–	–	10
		Nicarbazin	6	28.57	37.46	18.72	73.33	10
		Robenidine	1	4.76	14.95	–	–	10
		Salinomicin	2	9.52	27.35	17.72	36.98	10
		Senduramycin	1	4.76	11.77	–	–	10
		Trimethoprim	10	47.61	107.35	11.67	180.83	10
Parasiticides	Swine	Ivermectin (liver)	4	100.00	30.79	19.86	57.29	15
	Bovine	Abamectin	11	11.70	327.23	148.33	678.05	100
		Doramectin	8	8.51	169.02	113.17	245.20	100
		Fipronil (muscle)	1	5.32	20.3	–	–	10
		Fipronil (liver)	4		186.77	154.11	247.24	100
		Ivermectin (liver)	67	74.47	257.31	116.41	778.00	100
		Ivermectin (muscle)	3		80.77	18.00	204.00	10
	Milk	Abamectin	1	6.67	13.51	–	–	10
		Albendazole	1	6.67	221.51	–	–	100
		Doramectin	1	6.67	19.07	–	–	15
		Ivermectin	11	73.33	22.30	12.38	38.31	10
		Fipronil	1	6.67	42.70	–	–	20
	Equids	Doramectin	5	83.33	116.11	73	244.8	10
		Ivermectin	1	16.67	289.82	–	–	100

*Maximum Residues Limit (μg/kg); (n) Number of samples.

veterinary medicine to treat several diseases, but there is a potential risk for consumers, and therefore, it should be monitored to avoid its occurrence in animal products (Virginia 2015).

Zeranol was identified in non-compliant samples for bovine and equids chains related to a group of anabolic substances. There is no approval in Brazil for the use of these anabolic substances, such as growth promoters in livestock, and the occurrence of these substances must be investigated in another subprogramme of the PNCRC to determine where these substances originated from. When illegal veterinary medical products are used in husbandry, they often lead to fraud issues such as adulteration, and they are considered food fraud once they have been used deliberately (Spink and Moyer 2011).

The presence of beta boldenone in non-compliant samples from the swine chain ($n = 9$) was considered endogenous production, and there was no indication of illegal use, according to reports from PNCRC. Despite the possibility that the boldenone residues or its metabolites have been produced because of illicit use, there is also a possibility that this compound may be produced by endogenous sources, such as phytosterols in dietary fat used for feeding animals and possessing naturally occurring boldenone forms (De Brabander et al. 2004).

In broiler and swine chains, there were a greater number of non-compliant samples from antimicrobials with doxycycline, enrofloxacin, and oxytetracycline residues. Additionally, sulfamethazine was found in the swine and egg chains, while dihydrostreptomycin was found in the swine and equine chains (Table 4). In general, the antimicrobial category is dominated by antibiotics, which are mainly used in some of these chains, such as swine and broiler production as growth promoters.

Chloramphenicol, despite being prohibited in livestock, was detected in non-compliant samples in the broilers, fish, milk chains. Because of its genotoxicity, embryotoxicity, carcinogen effect, and aplastic anaemia, chloramphenicol is banned for use on food-producing animals in many countries (Novaes et al. 2017; Develos and Porticos 2019; Lees et al. 2021). Despite the prohibition of its use, these veterinary drugs are still used as an antibiotic in food-producing animals, which poses a public health risk to consumers of these products, demonstrating the necessity of educating farmers about the risks and hazards to consumers' health. The occurrence of chloramphenicol has been reported in different products from other countries. In the Philippines, Develos and Porticos (2019) reported that 11 out of 84 samples (13%) tested positive for chloramphenicol residues in retail chickens in Davao city. Wang et al. (2021) reported the detection of chloramphenicol in fish, pork, and poultry meat in 248 out of 1,454 samples (17.1%). Niang et al. (2017) reported that 32 out of 41 milk samples collected and analysed in Senegal contained chloramphenicol residues (78.0%). As a result, the period analysed by PNCRC for the prevalence of substances related to the amphenicol group showed a lower occurrence of chloramphenicol in Brazil, with 0.5% in the broilers chain (1 out of 2,040 samples), 0.1% in the fish chain (1 out of 1,223 samples), and 0.4% in the milk chain (1 out of 2,376 samples). The comparison between the results from PNCRC in Brazil and those in the literature from other countries for chloramphenicol shows a higher safety of Brazilian products in every chain.

Florfenicol was another compound that belongs to the amphenicol group found in

Table 4. Antimicrobial substances identified by chains in non-compliant animal-derived samples in Brazil from 2010 to 2021).

Chains	Compound	n	%	Means	Minimum	Maximum	MRL*
Broilers	Chloramphenicol	1	4.76	0.39	–	–	0.1
	Doxycycline (kidney)	2	33.33	4550.87	2269.50	6832.24	600
	Doxycycline (muscle)	5		397.68	174.15	874.67	100
	Enrofloxacin	3	14.29	440.50	123.00	635.34	100
	Oxytetracycline	1	4.76	241.67	–	–	200
	Semicarbazine	1	4.76	1.33	–	–	1
	Sulfamethoxazole	1	4.76	420.40	–	–	100
	Sulfaquinoxaline	7	33.33	1745.57	150.00	9999.99	100
Eggs	Ciprofloxacin	5	13.51	94.96	16.13	268.50	10
	Clopidol	1	2.70	14.77	–	–	10
	Enrofloxacin	22	59.46	149.97	13.73	1309.33	10
	Florfenicol	1	2.70	11.78	–	–	10
	Sulfachlorpyridazine	1	2.70	1354.67	–	–	10
	Sulfadiazine	1	2.70	18.02			10
	Sulfamethazine	6	16.22	28.93	12.99	84.03	10
Equids	Dihydrostreptomycin	1	14.29	73.60	–	–	50
Fish	Chloramphenicol (farmed fish)	1	7.14	75.61	–	–	0.3
	Malachite Green (farmed fish)	2	14.29	1.97	1.95	1.99	0.5
	Nitrofurazone/Semicarbazide (farmed fish)	10	71.43	2.24	1.35	4.17	1
	Oxytetracycline (farmed shrimp)	1	7.14	2188.40	–	–	100
Honey	Furazolidone	1	14.29	3.54	–	–	1
	Nitrofurazone	5	71.43	5.95	1.68	20.7	1
Milk	Cefalexine	1	3.70	139.75	–	–	100
	Cefoperazone	3	11.11	155.70	116.34	207.00	50
	Ceftiofur	1	3.70	144.00	–	–	100
	Chloramphenicol	1	3.70	0.65	–	–	0.3
	Cloxacillin	3	11.11	158.76	63.20	305.77	30
	Florfenicol	8	29.63	20.73	10.43	32.96	10
	Oxytetracycline	1	3.70	981.03	–	–	100
	Spiramycin	5	18.52	976.61	468.92	1563.09	200
	Tilmicosin	4	14.81	122.56	84.84	160.27	50
Swine	Ciprofloxacin	1	2.44	214.26	–	–	100
	Dihydrostreptomycin	3	7.32	5421.177	1705.73	7311.86	1000
	Doxycycline (kidney)	6	34.15	1029.033	782.17	1534.79	600
	Doxycycline (muscle)	8		269.1513	151.19	610.69	100
	Enrofloxacin	6	14.63	335.275	136.3	625.82	100
	Lincomycin	3	7.32	2222.88	1775.72	2855.83	1500
	Oxytetracycline	1	2.44	175.9	–	–	100
	Sulfamethazine	11	26.83	660.1845	131	2068.5	100
	Tilmicosin (kidney)	1	4.88	1243.6	–	–	1000
	Tilmicosin (muscle)	1		131.18	–	–	100

*Maximum Residues Limit (µg/kg); (n) Number of samples.

samples of non-compliant samples from milk (0.3%, 8 out of 2,376) and eggs (0.1%, 1 out of 2,063) chains. Even though this antibiotic has veterinary recommendations for treating certain diseases, it is banned during egg laying and should be used correctly in other chains to avoid this substance in products.

Additionally, banned in Brazil for use in food-producing animals, nitrofurazone and furazolidone were found in samples taken from the honey and fish chains (farmed fish) (Table 4). In farmed fish, nitrofurazone has been used against many fish diseases due to its efficiency in eliminating gram-positive and gram-negative bacteria (Almeida et al. 2009). This substance belongs to the group of nitrofurans and has been prohibited from being used in food animals in many countries since 1998 due to its toxic, carcinogenic, mutagenic, genotoxic effects and allergic reactions in hypersensitive individuals (Bayou and Haile 2017; Ramos et al. 2017). However, the occurrence of nitrofuran was reported by Lima et al. (2020) in honey samples in Brazil, indicating contamination of the substance. The reason for the occurrence of these compounds may lead to the misuse of these products because of a wide spectrum of action against certain diseases that occur in animal husbandry and attempt to be controlled by producers who are unaware of the restrictions on their use.

In the fish chain, the presence of oxytetracycline was also found in farmed shrimp (Table 4). The presence of this compound was also reported by Bortolotte et al. (2021) in tilapia fillet samples in Brazil, as well as the presence of florfenicol and enrofloxacin. However, all these antibiotic concentrations were below the MRLs. Therefore, aquaculture practices must be correctly applied, and farmers should be aware of avoiding the occurrence of these substances in fish products.

Among the samples analysed in the group of antimicrobials, malachite green residues were found in the fish chain (Table 4). Apart from its therapeutic use in aquaculture to treat bacteria, fungi, protozoa, and ectoparasites, this substance is not allowed in food-producing animals due to its carcinogenic, mutagenic, and genotoxic effects on humans and fish (Almeida et al. 2009; EFSA Journal, 2016). However, due to its high efficacy, low cost, availability, and lack of substitutes, it continues to be illegally used in aquaculture and poses a potential health hazard to humans when it is present in foods; and has been banned from use in many countries since 2002 due to toxic effects on fish and mammals (Almeida et al. 2009; Lee et al. 2010).

Although the number of non-compliant samples in Brazil detected for banned antibiotics in food animals was smaller, the occurrence of these substances is a concern because of the risk to consumer health. Islam et al. (2014) examined the possible source of contamination by nitrofuran and chloramphenicol in shrimp chain products and reported that the problem was associated with the source of feedstuff, where analysis of 160 samples found 38 to be contaminated with 3-amino-5-morpholinomethyl-2-oxazolidinone, 3-amino-2-oxazolidinone, 1-amino-hydantoin, semicarbazide and chloramphenicol. These results reinforce the care and importance of identifying the source of the problem in each chain in Brazil to prevent this occurrence and protect consumers. Therefore, the problem of these substances in products could be related to incorrect antibiotic therapy, i.e. use of products that should not be used on food animals, in addition to the lack of control over the source of feed and purchase of feed contaminated with these substances (McEvoy 2002).

Compounds from different antibiotic classes were identified in each chain (β-lactam, fluoroquinolone, tetracycline, sulfonamide, pyrimidine, cephalosporins, etc.), and many of them are allowed to be used in veterinary drugs in animal husbandry to treat diseases and infection (Hornish and Kotarski 2002; Daeseleire et al. 2017). Samples from the milk chain showed the presence of spiramycin, cloxacillin, cefalexin, cefoperazone, ceftiofur, oxytetracycline, and tilmicosin. Additionally, the lincomycin and tilmicosin residues were found in the swine chain, as well as sopharbazine, sulfamethoxazole, and sulfaquinoxaline in the broilers chain; and ciprofloxacin, chloridol, sulfachlorpyridazine, and sulfadiazine in the eggs chain (Table 4).

A total of 4,147 samples were analysed by PNCRC to screen for antimicrobial residues in the milk chain, and 27 samples (0.7%) had these

Table 5. Level of times over the maximum residue limits (MRLs) for non-compliant animal-derived samples in different chains and group of substances in Brazil (2010 to 2021).

Parameters		Average level of times over to MRLs	SEM	Minimum	Maximum
Chains*	Bovine	5.30[b]	2.17	1.04	338.7
	Broilers	4.97[abc]	1.74	1.14	100
	Eggs	11.62[a]	3.33	1.17	135.47
	Equids	4.46[abc]	1.36	1.10	24.48
	Fish	3.89[bc]	1.36	1.01	252.03
	Honey	4.46[abc]	2.34	1.14	20.7
	Milk	3.03[bc]	0.32	1.04	10.19
	Sheep/Goat	1.20[c]	0.00	1.20	1.20
	Swine	3.30[bc]	0.43	1.04	20.69
Group of substances*	Anabolic substances	5.48[bc]	1.54	1.25	20.16
	Antimicrobials	8.91[b]	2.29	1.04	252.03
	Beta-agonists	24.57[a]	16.68	1.08	338.7
	Chemical compounds	2.43[c]	0.56	1.14	5.13
	Coccidiostats	4.09[bc]	0.57	1.17	18.08
	Heavy metal	2.31[c]	0.11	1.01	10
	Parasiticides	2.99[c]	0.3	1.10	24.48

*LSD Test ($p < 0.05$), SEM = Standard Error of Mean.

substances present above the MRLs. Valença et al. (2021) reported a similar rate when analysing 184 raw milk samples when screening for the presence of 31 antimicrobial residues from six different groups according to parameters established by the PNCRC. These authors found one sample with the presence of cloxacillin above the MRL, which represented a rate of 0.5%. In the same way, other studies have examined the presence of antibiotic residues in milk samples acquired from commercial sources in Brazil, and these compounds were not detected over the MRLs (Novaes et al. 2017; Silva et al. 2021). Consequently, this result of PNCRC shows the safety for Brazilian dairy products with a low risk of violation for occurrence of veterinary drugs in products.

For the broilers chain, the results of PNCRC analysis revealed a total of 35,485 samples collected and analysed over 11 years for coccidiostat residues; only 53 (0.15%) were non-compliant samples with violations of the MRLs. The results from different authors confirm the safety of Brazilian chicken products. In 25 samples analysed, Mahatmi et al. (2019) found fluoroquinolone and tetracycline residues in low concentrations (below MRLs) in chicken meat imported from Brazil. Barros et al. (2021) searched for other veterinary drugs not covered by PNCRC (amoxicillin, bacitracin, colistin, dinitolmide + zoalene, spectinomycin, roxarsone, tiamulin, tylosin, trenbolone acetate, virginiamycin and halofuginone hydrobromide) in 2580 samples from chicken meat, and they did not find the occurrence of these compounds over the MRL according to parameters of worldwide legislation.

The results of the comparison according to the level of violation of MRLs in each chain and group of substances (veterinary drugs and contaminants) are shown in Table 5. Statistical analyses could not be conducted for three different groups of substances (i.e. anti-inflammatory, dioxin, and mycotoxin) due to an insufficient number of samples to compare. A statistical analysis found no significant interaction between substance groups and chains ($p = 0.057$). However, there were differences in the type of substance ($p = 0.016$) and food chain ($p = 0.004$).

Although there are violations and the presence of veterinary drugs and contaminants in foods, the concentration of these substances is extremely important. In Brazil, the eggs chain had a higher average rate at 11.6 times up to the MRL for substances searched at PNCRC. It was followed by a group of bovine, broiler, equid, honey, fish, swine, and milk chains; while the lowest result was found in the sheep/goat chain.

The highest level of violation was found concerning beta-agonists, which reached 24.6 times the MRLs, followed by antimicrobials, anabolic substances, coccidiostats, and other compounds belonging to the parasiticides, pesticides, and heavy metals group.

The results from PNCRC in Brazil demonstrate that the level of substances in products varies based on chains and type of substance, and the concentrations were 1.0 to 338.1 times greater than the MRLs. The concentration of these substances and the frequency of consumer exposure to them can promote harmful effects on human health.

In general, the results of PNCRC in Brazil over 11 years show the correct use of good practices in the sector of animal husbandry. Despite some risks related to the presence of substances in non-compliant samples in Brazilian products, they differ from chain to chain, and in general, the rate of compliance samples is above 99.5% for animal products, which make up approximately 86% of the total products originating from Brazil's primary sector. Each chain has followed the policies regarding the levels and withdrawal periods of veterinary drugs, and precautions regarding contamination sources and animal feed quality have been taken into consideration. Thus, even the low number of samples found with the use of substances that are forbidden or not recommended in food animals is an important indicator that improvement needs to be made together by farmers and professionals who are working in these chains.

Our findings refer to the result of monitoring of industries under SIF and it shows an effective service that the Brazilian agency (MAPA) has made to ensure the quality and safety of Brazilian products in this aspect. However, there are a large number of other industries under different inspection systems at a regional level regulated by states and cities that supply food to the Brazilian population following MAPA policies and could not have all their products monitored according to PNCRC. Despite creation of National Council for Food and Nutritional Safety created in 2006 by Law n°11,346 (Brasil 2006), where an adoption of good practices is mandatory to ensure a sanitary, safety, and environmental conditions for the production of food; it is necessary to expand this monitoring programme for all of them aiming to verify that good agriculture practices have been followed in every animal food chain, and Brazilian population have access to healthy and sustainable food.

Along with the animal chains, some points could be improved, mainly the problem with heavy metals in the fish chain, and the incidence of antibiotics and coccidiostats that have been misused, including the presence of forbidden substances. Through the proper use of good practices, it is possible to guarantee food safety for Brazilian products on international markets and to consumers throughout the world. According to the prevalence of non-compliant samples with veterinary drug residues and contaminants in many chains, Brazilian animal products can be considered safe.

Conclusions

The results indicate that the occurrence of non-compliant samples considering all types of animal products has been steady and low, and some risks are related to specific chains and types of substances and contaminants, and these problems will have to be handled in the next years to ensure the food safety of products for the Brazilian population and international markets.

The most frequent problem of contaminants in different chains includes the occurrence of heavy metals in animal products, such as cadmium in the bovine chain, and arsenic in the fish chain (mainly in wild fish); while a problem with veterinary drugs is associated with the occurrence of antimicrobials in swine and egg chains; coccidiostats in the broiler chain; and parasiticides in the bovine chain.

The number of accidental incidents including those associated with environmental contaminants has decreased over the last decade, as opposed to those involving human involvement such as deliberate illegal actions and abuse of veterinary drugs, have increased.

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Disclosure statement

The authors declare that there are no conflicts of interest.

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