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An overview of vinasse pollution in aquatic ecosystems in Brazil

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Abstract
We review the negative impacts of vinasse, a byproduct of alcohol distillation, on Brazil's freshwater ecosystems. We found a total of 37 pollution events between the years 1935 and 2023, with this number almost certainly an underestimate due to underreporting and/or unassessed events. Pollution by vinasse occurred both through accidents (e.g., tank failure) and deliberately (i.e., opening of floodgates), although in many cases the causes remain undetermined. All pollution events caused fish kills, with some records reporting negative effects on other organisms as well (i.e., crustaceans and reptiles). Pollution by vinasse, and associated negative effects, was reported for 11 states, with a notable number of cases in São Paulo. Most cases of vinasse pollution and negative impacts on biodiversity were recorded in rivers, followed by streams and reservoirs. Some of the affected river systems harbour threatened freshwater fishes. Hydrological connectivity means that pollution could have propagated along watercourses. Given these consequences of vinasse pollution on biodiversity, ecosystem functioning and services, we recommend a number of remedial actions.

Keywords Alcohol · Dissolved oxygen · Fishes · São Paulo · Stillage · Sugarcane industry

Introduction

Brazilian freshwaters are renowned for their high taxonomic, genetic, functional, and ecological biodiversity (Agostinho et al. 2005; Brito et al. 2020; Martins et al. 2020; Dias-Silva et al. 2021). For example, more than 3 000 species of freshwater fish have been described (ICMBio 2018). However, this diversity has been progressively eroded, leading to the rapid loss of populations and species (Pelicice et al. 2017; Albert et al. 2021). Habitat destruction and degradation are major drivers of this loss, but pollution also plays an important role (e.g., Fernandes et al. 2016). Some pollutants, such as fuels, crude oil, vinasse, and pesticides are well known to have adverse effects on freshwater biodiversity (e.g., Rezende 1984; Azevedo-Santos et al. 2022). This subject has received attention from researchers (e.g., Fraga et al. 2024), but important gaps persist in scientific literature.

Vinasse, a byproduct of the alcohol industry produced in numerous countries, originating especially from sugarcane (Almeida 1955; Silva et al. 2007), is characterized by the presence of a cocktail of chemical compounds, including phosphorus (e.g., Rezende 1984; Silva et al. 2007). It is likely to have multiple effects on aquatic biodiversity, as laboratory studies have shown detrimental effects on the morphology (Correia et al. 2017) and behavior of organisms (Silva et al. 2015). In addition, mortality events have been observed in places where vinasse is dumped (Almeida 1955).

Although leaks of vinasse into the natural environment have been reported in Brazil (Rezende 1984), the chronology and causes of each event of contamination, as well as its toxic effects of these on aquatic organisms, have not been systematically examined. The most comprehensive study to date, produced by Rezende (1984), is old and was not focused on freshwater biodiversity. Other studies (e.g., Christofoletti et al. 2013; Fuess et al. 2017) present the negative impacts of vinasse—but not filled this gap.

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Sugarcane plantations and the alcohol industry play an important role in the economy of Brazil (Valdes 2011). For example, in the fourth report of the year 2023, Conab (2023) showed that São Paulo State alone produced almost 12 billion liters of alcohol, resulting in a high vinasse production. There is therefore a pressing need to improve our understanding about the interaction of vinasse with aquatic environments and biodiversity. Our aim here is to review vinasse pollution events in Brazilian freshwater ecosystems. We start with a brief overview of vinasse and describe its production and main pathways into aquatic environments, along with its effects on freshwater biodiversity. We also provide some recommendations for a more sustainable alcohol industry.

The vinasse

Alcohol production in Brazil is primarily dependent on sugarcane (genus *Saccharum*), or its derivatives (Almeida 1955), though other vegetables such as sweet potatoes and beets can also be used (Silva et al. 2007; 2017). The liquor produced following fermentation is separated to yield both alcohol and vinasse (Almeida 1955; Prada et al. 1998)—the latter considered a byproduct. On average about 12 liters of byproduct (i.e., vinasse) are obtained when a single liter of alcohol (ethanol) is manufactured (Granato and Silva 2002). In the fourth report of the year 2023, Conab (2023, p. 39, our translation) stated that "the production of ethanol derived from sugar cane reached 27.37 billion liters in the current harvest (…)", which means that at least 328 billion liters of the byproduct have been produced in a single harvest.

Vinasse, including vinasse produced in Brazil, contains calcium, phosphorus, nitrogen, potassium (Almeida 1955). It is acid, with pH values ranging from 3.7 to 5.0 (Prada et al. 1998) and can exhibit chemical and biochemical demand (Prada et al. 1998; Carrilho et al. 2016; Fraga et al. 2024; see these references for more details on compounds). These latter attributes impact the availability of dissolved oxygen when the substance is released in the aquatic ecosystems. In addition, studies have shown the presence of numerous other compounds, including heavy metals (but in different concentrations) (Carrilho et al. 2016; Cotta et al. 2023). It is important to highlight that the precise chemical composition of vinasse depends on the precise manufacturing process employed (Almeida 1955).

In Brazil, alcohol and, consequently, vinasse, are produced in more than 15 states. According to a recent survey (Conab 2023), São Paulo and Goiás are the main suppliers of alcohol and, therefore, presumably the main producers of vinasse in the country. However, we found no published data on the volume of vinasse produced by each Brazilian state, although data on ethanol production is available (see Conab 2023).

Chronology of pollution

Drawing on different database sources and keywords in a search (see Methods in Supplementary Material 1), we found 37 reported events (i.e., occurrences) of vinasse pollution with lethal effects on aquatic organisms (Table S1 in Supplementary Material 1). Seventeen of these were described in technical reports, 12 in newspapers, six in scientific articles, one in the Official Diary of the Federal Chamber of Deputies of 1973, and one in a policy bulletin (Table S1 on Supplementary Material 1). We believe the number of reports found is underestimated, particularly due to the occurrence of events of pollution that were not reported or even assessed by authorities; limited access to some gray literature is likely a reason for under-reporting.

Reports of negative impacts of vinasse date from 1935 to the present day (2023) (Fig. 1). In the past, vinasse was deliberately released into aquatic ecosystems (see also Fernandes Filho and Araujo 2016), making it impossible to recover details about the resulting impacts. For example, the Decree number 23,777, of 1934, instructed the release of vinasse by stating "Art. 1° Fica estabelecida a obrigatoriedade do lançamento dos resíduos industriais das usinas açucareiras nos rios principais, longe das margens, em logar [lugar] fundo e correntoso [lótico]" (Brazil 1934, p. 2114) ["Art. 1° It is established the obligation of the discharge of industrial residues from the sugar industries in the main rivers, far from the margins, and in deep sites with flowing water" (Brazil 1934, p. 2114, our translation)]. Thus, rivers have served as the legal destination of vinasse, with no environmental concerns identified or reported. Subsequently, occasional mentions exist in contemporary political communication documents. A report in the National Congress Diary of 1973 expressed concern about the mortality of aquatic organisms in the Pardo River and its tributary, the Mogi-Guaçu River (Brazil 1973), Upper Paraná River system. From the second half of the 1970s, the pollution of aquatic ecosystems by vinasse was prohibited by national authorities (Fernandes Filho and Araujo 2016).

Most records of vinasse pollution we found are recent, being recorded after the 2000s (Fig. 1). The trivialization of pollution events in the past, combined with limited inspections and legislation that allowed vinasse disposal, along with scant information about environmental issues, likely explain the lack of earlier reports. One exception is Rezende (1984), who recorded some old cases based on newspaper information. Although we were unable to find the original sources (i.e., newspapers), this reference provides crucial evidence that vinasse pollution was

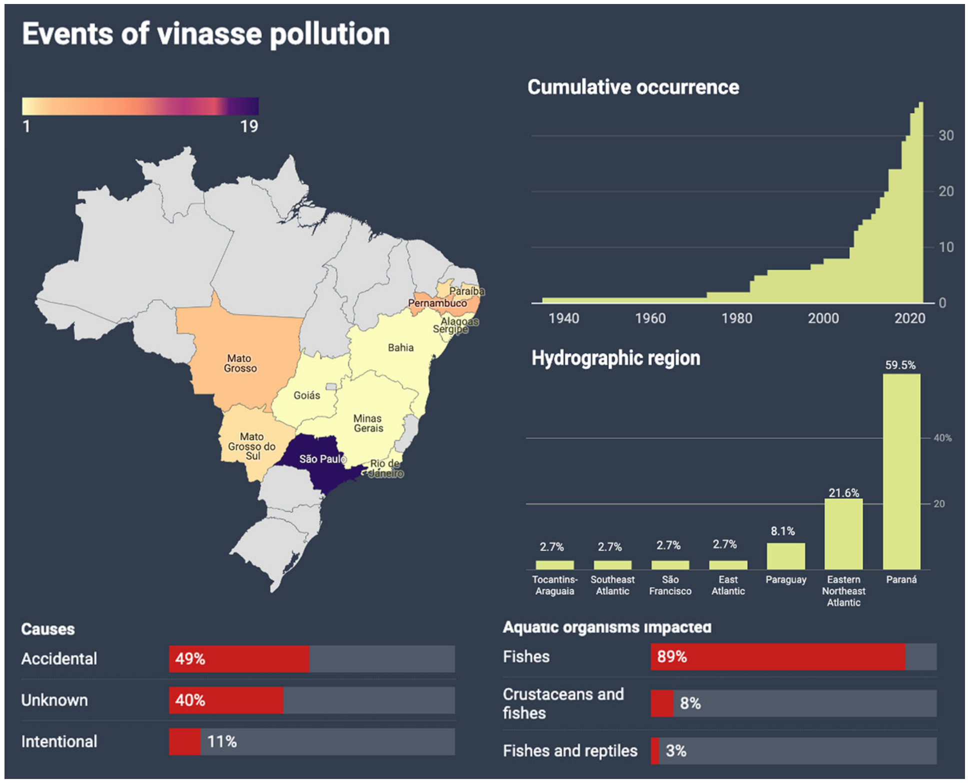

Fig. 1 Pollution events by vinasse with negative effects on freshwater biodiversity, based on Supplementary Material 1

commonplace in the past, when events were poorly monitored or recorded.

Pathways to the environment

According to the records we found, vinasse has reached waterbodies mainly through accidental release, although deliberate dumping (i.e., intentional) also occurred. However, in many cases the causes were not documented (Fig. 1).

In the case of accidental pollution, vinasse leaks were attributed to ruptures in the structures used to transport the byproduct (CETESB 2015), or to the collapse of dams, or other structures used to store vinasse (Table S1). Another source of accidental release has been farming activities (Table S1) because vinasse, rich in nutrients, is used as a fertilizer (Baffa et al. 2009). A report also indicate leaks during road transportation (Table S1), a pathway with considerable potential to negatively impact watercourses and other aquatic ecosystems (Azevedo-Santos et al. 2022).

Deliberate releases were relatively less common, likely because current regulations—which are sparse, but exist (Fernandes Filho and Araujo 2016)—govern how the alcohol industry deals with vinasse. The most recent reports (i.e., between 2000 and 2023; Table S1) focus on clandestine and illegal disposal. Some reports indicate that clandestine releases still occur in rivers (Table S1), possibly at night, to avoid inspections.

Cases of pollution where the causes are unknown may be related to accidental or clandestine releases. However, diffuse releases make it very difficult to identify the cause of these pollution events.

Negative effects of vinasse pollution

All 37 events of vinasse pollution reported fish mortality, while other groups, such as crustaceans and reptiles, were mentioned occasionally (Fig. 1). None of the reports provided scientific identification of species. Brazilian watercourses, in general, support rich biodiversity in addition to crustaceans, fishes and reptiles (e.g., Segura et al. 2007; Galliez et al. 2009; Picapedra et al. 2019; Linause et al. 2020). Accordingly, the lethal consequences on these three groups—especially fish—suggest that other aquatic organisms (e.g., zooplankton, insects, amphibians, plants) may be also affected by vinasse pollution to some extent. This conclusion is well supported by many scientific studies on vinasse pollution (e.g., Pinto et al. 2021; Silva et al. 2021; Fraga et al. 2024). For example, Almeida (1955) argued vinasse can severely impact aquatic invertebrates, including planktonic organisms. Indeed, Botelho et al. (2012) found in an experiment that relatively lower concentrations of vinasse are sufficient to kill microcrustaceans (i.e., *Ceriodaphnia dubia* Richard 1894 and *Daphnia magna* Straus 1820) when compared to the response of a fish species [i.e., *Danio rerio* (Hamilton 1822)]. Other vertebrates (i.e., amphibian larvae) exposed to the vinasse also experienced lethal effects (Freitas et al. 2022). Furthermore, mortality of *Lemna minor* (L.) in experimental trials (Silva et al. 2015), indicates that vinasse is lethal to plants too. Here it is important to mention that other studies show sublethal effects in experimental conditions (e.g., Fraga et al. 2024). Although these lie outside the scope of this study, we do not dismiss the importance of sublethal effects on organisms in natural watercourses impacted by vinasse.

Mortality of the three biological groups identified in our search (i.e., crustacean, fishes, and reptiles) may be associated with different ramifications of vinasse pollution. A total of 19% of the reports attribute animal deaths to depletion of dissolved oxygen (Table S1). Although the remaining records (81%) provide no information on the reason why vinasse pollution led to mortalities a short term decrease in dissolved oxygen could be the main cause. In addition, a decrease in pH levels, as shown by laboratory experiments carried out with invertebrates and vertebrates (Botelho et al. 2012), may have played a role. In the longer term, the release of nutrients associated with vinasse, especially nitrogen and phosphorus (Prada et al. 1998), may increase eutrophication (Strapasson and Job 2006; Rosa and Martins 2013; Moran-Salazar et al. 2016; Hoarau et al. 2018), and impact algae blooms, biomass accumulation, decomposition, and dissolved oxygen (Aguiar et al. 2011). These consequences may be implicated in the mortalities we uncovered.

In Brazil, pollution by vinasse and associated mortality events were reported for 11 states, encompassing several waterbodies in different river basins. Most events occurred in the southeast, particularly in São Paulo (Fig. 1), notably in the upper Paraná River basin (Fig. 1). This trend is probably associated with the concentration of sugarcane industry in the southeast region (224 plants *sensu* Nova-Cana 2023). The presence of the Environmental Company of the State of São Paulo (CETESB) must also be considered, given its extensive experience in conducting inspections, monitoring, and documentation of pollution events—which may add some bias to our results. Currently, 18 Brazilian states produce alcohol (Conab 2023) and consequently vinasse, indicating that pollution events may be more widespread than our survey suggests. The absence of reports in some states and drainages may be explained by the lack of monitoring or limited access to technical reports.

Most cases of vinasse pollution and negative impacts on biodiversity were recorded in rivers (51.4%), followed by streams (24.3%) and reservoirs (13.5%). Some reports (10.8%) included both streams and rivers (Table S1). Streams and rivers are home to many threatened species (e.g., Deprá and Slobodian 2024), which are present in some rivers affected by vinasse (Table 1). In the São Francisco River, for example, ~300 tons of organisms were killed with the release of ca. 45,000,000 liters of vinasse (Rezende 1984). One of the affected species is the "surubim" (Rezende 1984), possibly the catfish *Pseudoplatystoma corruscans* (Spix & Agassiz 1829), a species currently listed on the national Red List (MMA 2022).

Pollution events have great potential to propagate across the river network. For example, we found that vinasse reached downstream sites in the Corumbataí River from the Tamandupá stream (Table S1). Another case was the pollution of the Aguapeí River through its affluent, the Sapé stream, an event that killed fish (and possibly other organisms) in both ecosystems (see Table S1). Similar cases have been reported in scientific literature for other pollutants (e.g., oil, ore waste), with directional impacts towards downstream areas (e.g., Escobar 2015; Fernandes et al. 2016; Azevedo-Santos et al. 2016; 2021). Teleconnection is indeed a main feature of river networks, whose effects constitute a major challenge to manage and preserve aquatic ecosystems (Azevedo-Santos et al. 2019)—particularly when the source of pollution is located upstream.

Negative impacts at the ecosystem level are more challenging to assess, primarily due to the lack of baseline information for periods preceding vinasse pollution. However, using fish as an example, the group with the most mortality records, we can infer that pollution by vinasse (Table S1) leads to changes in the food chain. Indeed, it is expected that pollution-linked perturbations in the food web will frequently reoccur (e.g., Azevedo-Santos et al. 2016; 2021). In addition, the loss of ecosystem services is inevitable. For example, negative effects of vinasse on fishing have been reported since the 1970s (Brazil 1973). A more recent case (from 2007) has shown that indigenous communities and other traditional groups were adversely affected by vinasse (MP 2010), probably due to the loss of fishing resources. Considering the importance of fish for humans (Pelicice et al. 2023), we believe that these losses of ecosystems services were frequent occurrences.

Most reports of animal deaths included here are recent (2000–2023), probably due to the expansion of the industry, changes in environmental legislation, and increased inspections. However, it is likely that aquatic biodiversity has been continuously impacted by vinasse in the preceding years when inspections and monitoring were infrequent. This scenario raises some questions: Did some fish species (and other groups) become locally or regionally extinct before they were formally named? Has vinasse contributed to the decline of species or collaborate to threaten them with extinction? How often has vinasse contributed to the loss of fishery resources? The hidden nature of vinasse pollution makes it difficult to answer these questions, because the manner in which this pollutant contributed to the loss of aquatic biodiversity in the past remains poorly known (i.e.,

Table 1 Threatened freshwater fishes with records in rivers (or areas with influence of them) affected by vinasse

ORDER/Family/*species*	Watercourse	Category	Voucher
CHARACIFORMES			
Serrasalmidae			
Myloplus tiete (Eigenmann & Norris 1900)	Mogi-Guaçu River	EN	LIRP 14989
Prochilodontidae			
Prochilodus vimboides Kner 1859	Aguapeí River; Mogi-Guaçu River	VU	MZUSP 3047; MZUSP 3434
Bryconidae			
Brycon orbignyanus (Valenciennes 1850)	Aguapeí River	CR	MZUSP 67070
SILURIFORMES			
Heptapteridae			
Chasmocranus brachynema Gomes & Schubart 1958	Mogi-Guaçu River	EN	EEBP 629
Pimelodidae			
Conorhynchos conirostris (Valenciennes 1840)	São Francisco River	EN	LIRP 18141
Pseudoplatystoma corruscans (Spix & Agassiz 1829)	Aguapeí River; Amambaí River; São Francisco River	VU	MZUEL 13408; NUP 17754; MBML 11409
Pseudopimelodidae			
Lophiosilurus alexandri Steindachner 1876	São Francisco River	VU	MZUSP 1160
CYPRINODONTIFORMES			
Rivulidae			
Hypsolebias gardneri Costa, Amorim & Mattos 2018	São Francisco River	EN	MZUEL 12856

Note: Vouchers are one or more representative individuals of each species deposited in biological collections. Methods, including definitions for the acrograms (e.g., EEBP), may be found in Supplementary Material 2

VU = Vulnerable

EN = Endangered

CR = Critically Endangered

silent losses and extinctions). This knowledge gap concerning past negative impacts, coupled with the documentation of more recent effects, emphasizes the imperative for improved monitoring, increased case studies, and targeted experiments. Additionally, there is in general a pressing need for better practice during the production and management of vinasse.

Recommendations for the near future

The situation regarding vinasse pollution in Brazil has improved significantly in recent years, considering that in the past it was deliberately released into streams, rivers, and other waterbodies without any control. However, given its high potential to cause negative impacts on aquatic ecosystems (e.g., Table S1), the disposal or reuse of vinasse needs more attention. This is especially important in the context of expansion of alcohol production in the country. Much greater governmental attention is warranted.

At present, there is no specific legislation concerning the management of vinasse at the federal level (Fernandes Filho and Araujo 2016). An important initiative in this regard was Bill 5,182/2013, which was considered a significant step forward (Fernandes Filho and Araujo 2016). For example, this Bill proposes the creation of the "Vinasse Application Plan", which "(…) will be used by the competent environmental body for the purpose of follow-up [monitoring] and inspection" (Brazil 2013, p. 4, our translation). Regular inspections across national territory could prevent negligence and accidental spills in plants or during transportation, as well as curb illegal releases. However, Bill 5,182/2013 was filed by the Chamber of Deputies (Brazil 2013). Since relevant legislation remains pending, a major gap in tackling the vinasse problem in the country remains unfilled. Such federal legislation, that may be an update by using points of Bill 5,182/2013, must address issues related to safe confinement, transportation, as well as regular inspections.

Changes in existing laws (with the presence of scientists in the discussions; see Azevedo-Santos et al. 2017) may also be a form to help a more secure use of the vinasse. For example, it is known that riparian buffers are important to protect watercourses from the pollution of the agriculture (Lowrance et al. 1984); this certainly includes the leaching of vinasse at the land-water interface in irrigated fields. Therefore, changes in Law 12,651 (Native Vegetation Protection Law; see Brazil 2012), expanding the stripes of Permanent Preservation Areas (APPs, in Portuguese) along watercourses of areas where vinasse is produced or used in irrigation—as well as demanding the clear recovery of riparian vegetation—could be a promising path.

Vinasse can be used in numerous products, such as for animal feeding, fuel, construction material and other uses (Montiel-Rosales et al. 2022). Currently, for example, there are technologies that transform this byproduct into biogas (Parsaee et al. 2019; Almeida and Rizzatto 2022). These technologies, with government assistance (specific credits) (see Fernandes Filho and Araujo 2016), could be developed and disseminated in numerous states of the country. However, it is essential to encourage the use of these technologies in the areas where vinasse is produced, to avoid transportation and the risk of accidents. Adding value to the vinasse could provide multiple uses and avoid deliberate (illegal) disposal in Brazilian watercourses.

Emergency actions to mitigate pollution effects are also need. In the case of pollution events, it is first necessary to locate the source of pollutants and then take the necessary measures to stop it. Subsequently, a multidisciplinary team should be engaged to assess the negative impacts of the pollution. This may be designated (i.e., chosen) by competent Brazilian authorities (e.g., judiciary) as a matter of urgency. In most of the pollution events found (Table S1), only the death of fish was documented. This is not an isolated problem as it occurs in numerous other pollution events in the country (Azevedo-Santos et al. 2022). Thus, in the case of vinasse, as in other pollution impacts, research effort in the assessment must consider freshwater biodiversity in its entirety as well as associated ecosystems services. Finally, responsible companies must be aware that in addition to paying fines (e.g., NovaCana 2022), they must restore the affected terrestrial and aquatic ecosystems. Such initiatives—which are not simple and can often be costly for the polluting company—reinforces the need for measures that prevent pollution events.

Conclusion

Our study provides an overview of the problem of vinasse pollution (especially in its present form) in Brazil. We found 37 pollution events, but we recognize that this number is underestimated. However, the findings reported here—i.e., chronology of the pollution occurrences, pathways of contamination, as well as the negative effects on Brazilian freshwater biodiversity and ecosystems services—are important to support the development of federal policies and other actions concerning the management of vinasse in the country. This is an urgent challenge given the expansion of the alcohol industry across the country.

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Compliance with ethical standards

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Consent to participate All authors consent with the content of the paper.

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