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Agrochemicals in Costa Rica's pineapple industry: A review of environmental and human health impacts

Agroquímicos en la industria piñera de Costa Rica: una revisión de los impactos ambientales y en la salud humana

Agrotóxicos na indústria do abacaxi na Costa Rica: uma revisão dos impactos ambientais e na saúde humana

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Abstract

This article focuses on the environmental and human health impacts of agrochemicals used in the production of pineapples (Ananas comosus) in Costa Rica. The pineapple production process involves several stages from cultivation to packing. Different types of inputs, such as agrochemicals, machinery, fuels, electricity, and water are known to be used along this production process. While the climate impacts and solid agricultural waste management of pineapple production in Costa Rica have recently been studied, the environmental and human health impacts of agrochemicals in the production process remain underexplored. We address this gap by reviewing articles and reports from academic databases, scientific journals, government reports, and reputable organizations. The review is organized around the key themes of pesticide residue contamination, environmental impact, human health implications, and societal response. It identifies risks to non-target organisms, ecosystems, and human health from pineapple production across different regions in Costa Rica. The findings are discussed in the context of other pineapple-producing countries globally to highlight potential leverage points to make pineapple production in Costa Rica more sustainable and support human health. Hereby, this study provides an up-to-date insightful analysis of the implications of chemical pollution in Costa Rican pineapple production industry. The findings underscore the importance of adopting more sustainable practices to mitigate environmental and health risks associated with this economically crucial agricultural industry. Moreover, a better understanding of the complex dynamics between agricultural practices, environmental sustainability, and public health is imperative to develop and implement adequate policy measures. As of now, there is insufficient systematic data and knowledge on the application of chemical substances along the pineapple production chain, which has to be addressed in the near future.

Keywords: Contamination, Environmental Impact, Human Health, Pesticides, Pineapple Cultivation

Resumen

Este artículo se centra en los impactos ambientales y en la salud humana de los agroquímicos utilizados en la producción de piña (Ananas comosus) en Costa Rica. El proceso de producción de piña comprende varias etapas, desde el cultivo hasta el empaque. A lo largo de este proceso se utilizan distintos insumos, como agroquímicos, maquinaria, combustibles, electricidad y agua. Si bien recientemente se han estudiado los impactos climáticos y la gestión de residuos sólidos agrícolas de la producción de piña en Costa Rica, los impactos ambientales y en la salud humana de los agroquímicos en este proceso siguen siendo poco explorados. Abordamos esta brecha mediante una revisión de artículos y reportes provenientes de bases de datos académicas, revistas científicas, informes gubernamentales y organizaciones reconocidas. La revisión se organiza en torno a los temas clave de contaminación por residuos de plaguicidas, impacto ambiental, implicaciones en la salud humana y respuesta social. Se identifican riesgos para organismos no objetivo, ecosistemas y salud humana derivados de la producción de piña en diferentes regiones de Costa Rica. Los hallazgos se discuten en el contexto de otros países productores de piña a nivel global, con el fin de destacar posibles puntos de intervención que permitan hacer la producción de piña en Costa Rica más sostenible y proteger la salud humana. De este modo, el estudio ofrece un análisis actualizado y revelador sobre las implicaciones de la contaminación química en la industria piñera costarricense. Los resultados subrayan la importancia de adoptar prácticas más sostenibles para mitigar los riesgos ambientales y sanitarios asociados a esta industria agrícola de gran relevancia económica. Además, una mejor comprensión de las complejas dinámicas entre las prácticas agrícolas, la sostenibilidad ambiental y la salud pública es fundamental para desarrollar e implementar medidas políticas adecuadas. Actualmente, existe una falta de datos y conocimiento sistemático sobre la aplicación de sustancias químicas a lo largo de la cadena de producción de la piña, aspecto que debe abordarse próximamente.

Palabras clave: Contaminación, Cultivo de piña, Impacto ambiental, Plaguicidas, Salud humana

Resumo

Este artigo enfoca os impactos ambientais e na saúde humana dos agrotóxicos utilizados na produção de abacaxi (Ananas comosus) na Costa Rica. O processo de produção do abacaxi envolve várias etapas, desde o cultivo até a embalagem. Diversos insumos, como agrotóxicos, máquinas, combustíveis, eletricidade e água, são utilizados ao longo desse processo produtivo. Embora os impactos climáticos e a gestão de resíduos sólidos agrícolas da produção de abacaxi na Costa Rica tenham sido estudados recentemente, os impactos ambientais e na saúde humana dos agrotóxicos nesse processo ainda são pouco explorados. Esta lacuna é abordada por meio de uma revisão de artigos e relatórios de bases de dados acadêmicas, periódicos científicos, relatórios governamentais e organizações de referência.
A revisão é organizada em torno de temas centrais como contaminação por resíduos de pesticidas, impacto ambiental, implicações para a saúde humana e resposta social. Identificam-se riscos para organismos não-alvo, ecossistemas e a saúde humana decorrentes da produção de abacaxi em diferentes regiões da Costa Rica. Os resultados são discutidos no contexto de outros países produtores de abacaxi no mundo, a fim de destacar pontos estratégicos para tornar a produção de abacaxi na Costa Rica mais sustentável e promover a saúde humana. Assim, este estudo oferece uma análise atualizada e esclarecedora sobre as implicações da poluição química na indústria abacaxícola costarriquenha. Os achados ressaltam a importância de adotar práticas mais sustentáveis para mitigar os riscos ambientais e sanitários associados a esta indústria agrícola de grande relevância econômica. Além disso, uma melhor compreensão das complexas dinâmicas entre práticas agrícolas, sustentabilidade ambiental e saúde pública é essencial para o desenvolvimento e implementação de medidas políticas adequadas. Atualmente, faltam dados e conhecimentos sistemáticos sobre o uso de substâncias químicas ao longo da cadeia produtiva do abacaxi, lacuna que precisa ser enfrentada em um futuro próximo.

Palavras-chave: contaminação, cultivo de abacaxi, impacto ambiental, pesticidas, saúde humana

Introduction

Pineapple production holds considerable economic importance in Costa Rica. Approximately 58.000 ha are dedicated to its cultivation as of 2019 (Sasa & Andraka, 2024), the sector provides employment for nearly 152.000 residents (Guirres et al., 2023). Most pineapple plantations are situated in the lowlands of the Northern Huetar Region (53%) and Caribbean Region (27%) as well as along the southern Pacific coast of the country (20%) (Cámara Nacional de Productores y Exportadores de Piña, CANAPEP, 2023). According to Brenes-Alfaro et al. (2021), Costa Rica holds the title of the world's largest exporter of fresh pineapple, contributing an estimated 1.7% to the nation's GDP (Chacón-Cascante, 2015). In 2021, pineapple production in Costa Rica amounted to almost three million tons. The growing demand for pineapples, both for local consumption and export, has led to an expansion of the sector to the northern border region with Nicaragua, particularly in the cantons of Los Chiles, Guatuso and Upala, which together produce approximately 53% of the country's pineapple output (Rodríguez Echavarría & Prunier, 2020; Valverde, Porras y Jiménez, 2016). Moreover, new varieties have been singled out for their contribution to improving production by utilizing pesticides and fertilizers (Ingwersen, 2012).

While the climate impact and the agricultural solid waste management resulting from pineapple production in Costa Rica have recently been investigated (González-Alfaro, 2012; Hernández-Chaverri et al., 2018; Jaikel-Víquez & Ulate-Brenes, 2021; Vargas-Vargas et al., 2019), the implications of the use of agrochemicals in the production process for the environment and human health remains underexplored. We address this gap based on a literature review. The review includes national sources as well as a global perspective by incorporating relevant studies from other pineapple-producing countries worldwide. The systematic search includes academic databases, scientific journals, governmental reports, and reputable organizations. The search criteria consider publications in English, Spanish, and Portuguese to ensure inclusivity. The literature review is organized around the key themes of pesticide residue contamination, environmental impact, human health implications, and societal response. Relevant publications exploring comparative analyses with other countries are included to enhance the global perspective. Patterns,

trends, and disparities in the use and implications of agrochemicals along the pineapple production chain across different regions in Costa Rica are thus identified. Furthermore, pathways are explored through which pesticides may enter the environment, posing risks to non-target organisms, ecosystems, and human health. The findings are discussed in the context of other pineapple-producing countries globally to highlight potential leverage points to render the Costa Rica pineapple production more environmentally benign and support human health.

Pineapple farming and the use of agrochemicals in Costa Rica

Pineapple production in Costa Rica began in the late 1970s, with initial exports by the company PINDECO (Del Monte) starting in the early 1980s. However, it was only in the early 1990s that pineapple cultivation gained popularity, exhibiting continuous growth (Blanco-Obando, 2020). Pineapple productivity witnessed a significant increase of 91% between 1991 and 2014, which can be attributed to improvements in the availability of inputs such as seeds, fertilizers, and herbicides (Rodríguez, 2015). Indeed, multinational studies position Costa Rica as the optimal country for pineapple cultivation, especially in the northern region, where artificial irrigation is unnecessary, and the production cycle is nine months ahead compared to other producing countries (CANAPEP, 2008). For instance, Malézieux et al. (2003) argue that pineapple is efficiently cultivated in a broad range from 30° latitude North to 33°58´ latitude South. In combination with the production cycle duration, encompassing planting and harvesting varying from 12 to 36 months, its favorable conditions make Costa Rica the world's largest producer. The primary pineapple cultivars grown today include Red Spanish, Queen, Smooth Cayenne, MD2, and Abacaxi (World Population Review, 2024).

The Costa Rican pineapple production process encompasses three stages. The cultivation stage (incl. harvesting) requires the use of agrochemicals (pesticides, herbicides, fungicides, and chemical fertilizers), machinery, fuels, and water. If not directly sold on local and regional markets, there also is a packaging process. This packing stage requires electricity, chemicals, and water, before distribution to retailing or further processing begins (Ingwersen 2012). While the agricultural solid waste

management resulting from pineapple production in Costa Rica and its impacts recently have been investigated (see e.g. Amores-Monge et al. 2012 for a review) and recycling opportunities for solid organic waste discussed, knowledge of the impacts of agrochemicals (i.e., pesticides and heavy metals) in the cultivation (incl. harvesting) and packaging stage remain scarce. Particularly in tropical areas, the problem of pesticide pollution and its impact on aquatic ecosystems is exacerbated by a combination of unfavorable conditions. The persistent wet and humid environment requires significant pesticide use throughout the year (Weiss, 2021).

According to the World Health Organization (WHO), pesticides are a distinct category of agrochemical substances designed to eliminate various pests, including weeds, insects and rodents (WHO 2017). Herbicides account for 47.5% of pesticide contributions, followed by insecticides 29.5%, fungicides 17.5%, and other types of insecticides 5.5% (Pathak et al., 2022). It is undeniable that the intensive cultivation of pineapple heavily relies on significant inputs of fertilizers and pesticides to sustain production levels (Bach, 2007; Blanco-Obando, 2020).

Pesticides pose significant challenges due to their primary purpose of inducing toxic effects in plants, fungi, and pest arthropods, though unintended impacts on non-target species frequently occur in agricultural fields (Pathak et al., 2022; Liess and Von der Ohe, 2005). The utilization of these chemical substances, coupled with soil overexploitation and inadequate waste management, has resulted in adverse effects on the environment, society, and human health. In fact, Costa Rica has the highest pesticide use per capita in Central America due to its intensive agriculture (Bravo et al. 2011; Staudaucher et al., 2022). Costa Rica uses between four and eight times more pesticides per hectare than other countries in the Americas that are part of the Organization for Economic Cooperation and Development (OECD), including Canada, the United States, Mexico, Chile, and Colombia (Pomareda García, 2022). While most of these countries use an average of 2 kilograms of active ingredient per hectare (kg ai/ha) of agricultural land (combining pasture and crops), Costa Rica records quantities exceeding 9.15 kg of active ingredient per hectare (kg ai/ha) (Ministerio de Agricultura y Ganadería, MAG, 2024).

Pineapple faces significant susceptibility to weeds due to its sluggish growth, shallow root structure, and limited competitive capacity. The technological package used in

the Costa Rican pineapple industry, that is known thus far, consists of a highly diverse set of agrochemicals (Astorga Gättgens, 2017). These include examples such as Bromacil, Diuron, Imidacloprid, and Propiconazole, among others.

Bromacil, for instance, was favored as an herbicide due to its effectiveness in managing various weeds. Bromacil was initially introduced into commercial markets in 1961 as an uracil herbicide with both pre- and early post-emergence activity against a variety of grasses and broadleaf weeds (Valverde & Chaves, 2020). Its primary applications are observed in pineapple, citrus fruits, and non-cultivated areas at doses from 1.6 to 3.2 kg ai/ha. A unique advantage of Bromacil is that it allows pineapple planting just four days after application. No other residual herbicide approved for pineapple cultivation permits planting within less than eight days post-application (Valverde & Chaves, 2020). The Central American Institute for Studies on Toxic Substances (IRET), identified Bromacil concentrations exceeding 5 µg L−1 in rivers, surpassing ecological safety limits for wildlife in regions impacted by pineapple cultivation (Castillo et al., 2009). Furthermore, IRET documented traces of organophosphate pesticides in rivers across the Caribbean region (Ugalde Salazar, 2007).

Another important pesticide in the pineapple production process is Diuron, which is classified as a phenylurea pre-emergence herbicide, and is known for its prolonged presence in soil. Its impact on the environment is considered moderate to significant across various taxa including birds, fish and bees. Imidacloprid, a neonicotinoid insecticide notorious for its detrimental effects on pollinator communities, faced a ban in the European Union in 2018 due to its persistence in soil, and high contact and oral toxicity toward bees and birds (Butler, 2018). In addition, propiconazole functions as a triazole fungicide, falling within the range of moderate to persistent pesticides, and chronic ecotoxicity in fish has been reported for this compound (Quirós, 2017).

Recent surveillance carried out between 2015 and 2018 in Costa Rica revealed the presence of 28 different pesticides in both surface and groundwater. Out of these substances, 16 are authorized for application on pineapple crops (Bolaños Picado et al., 2022). This aligns with previous findings highlighting significant threats to water quality due to agrochemical use in pineapple-producing regions (Hidalgo et al., 2019). Noteworthy is the complete prohibition of Bromacil in Costa Rica as of 2017,

mandated by decree N° 40423-MAG-MINAE-S (Costa Rica, 2017), because of its repeated detection during monitoring in groundwater samples.

Environmental impact & human health implications

Astorga Gättgens (2017) highlights that 80% of the known agrochemicals used in pineapple production is toxic, which poses a substantial contaminating impact on soil and water sources. The issue arises from the prolonged application of these agrochemicals throughout the entire "productive lifespan" of the pineapple cultivation area, which may span several decades. This practice results in a cumulative environmental effect, translating into contamination and environmental harm (Maglianesi-Sandoz, 2013).

The environmental impact of pineapple fields increases where pineapple plantations are located near rivers (Vargas Ramírez, 2007). Pesticide runoff from pineapple plantations may then cause a high toxicity risk to non-target species in rivers downstream the cultivation sites (Ammann et al., 2020; Arias-Andrés et al., 2016). Intense rainfalls, characteristic of Costa Rica's tropical climate, accelerates the runoff of soil particles and pesticides from agricultural fields into nearby rivers (Weiss, 2021; Castillo et al., 2006). Studies provide clear evidence indicating that pineapple production increases pesticide levels in water and affects Costa Rica's aquatic ecosystems. For instance, Echeverría et al. (2012) demonstrated the significant influence of pineapple plantations on aquatic ecosystems, resulting in poor plant growth, anticholinergic effects, and oxidative stress in fish populations. Moreover, after entering the environment, pesticides have the potential to undergo various transformation processes. These may involve changes induced by non-living factors like photo-degradation or hydrolysis, as well as alterations facilitated by living organisms, known as biotransformation (Weiss, 2021).

High concentrations of pesticides may also cause significant larger-scale environmental harm. For instance, in 2010, a substantial reduction in the diversity of forests and insects was observed in the vicinity of pineapple plantations in Costa Rica, accompanied by heightened concentrations of insecticides, fungicides, and pesticides in water sources (Programa Estado de la Nación, 2011). In 2017,

a significant incident of mass mortality among fish, crustaceans, and reptiles was documented in Laguna Madre de Dios, Bataán. This tragic event was linked to the pollution of the lagoon by fungicides such as Azoxystrobin, Epoxiconazole, Difeconazole, and Thiabendazole, as well as herbicides like Ametryn, Hexazinone, Diuron, and the insecticide Diazinon. Local residents assert that these substances originated from nearby plantations of banana, pineapple, and rice (Quirós, 2017).

Beyond their environmental consequences, pesticides are recognized as potentially hazardous substances for human health, requiring careful regulation and monitoring of their use and exposure (Sharma et al. 2020). Especially so-called persistent organic pollutants (POPs) are problematic and the Stockholm Convention on Persistent Organic Pollutants (2001) strictly regulates their use internationally. Prolonged exposure to these substances may result in their buildup within bodily tissues, causing adverse impacts on growth, development and metabolic functions (Shah, 2020; La Merrill et al., 2013). Pesticides have also been connected to various health disorders affecting the cardiovascular, central nervous, and respiratory systems (Sharma et al. 2020). In addition, when organic matter is burned, there is always a risk of generating POPs during the combustion process. According to Zhai et al. (2022), these pollutants and their precursor molecules can arise from unburned carbon fragments in the combustion gases as they cool.

Pesticide exposure can occur either as acute or chronic. Acute exposure refers to short-term contact with high pesticides concentrations, often resulting in symptoms like skin irritation, blisters, rashes, blindness, abdominal pain, diarrhea, or vomiting (Sharma et al., 2020; Thundiyil et al., 2008). Conversely, chronic exposure manifests over months or years, potentially leading to cancer, birth defects, reproductive issues, toxicities, or even death (Alavanja et al., 2004; Shah, 2020). Especially the chronic exposure to pesticides from pineapple production in Costa Rica becomes relevant for human health of the public through water pollution and high contamination levels in food products.

Chemical pollution of aquifers near the pineapple plantations poses an imminent threat to the health of the local population. With regards to pesticides in water supplies, the most conspicuous contamination of water sources by chemical residues reaching levels rendering the water unsuitable for human consumption,

was observed in the canton of Siquirres, specifically in the communities of Milano, El Cairo, La Francia, and Luisiana. In 2003, contamination of the local aquifer with Bromacil, Diuron, and Tridamefó - all agrochemicals commonly used in pineapple plantations - was identified. This incident resulted in the suspension of water services for approximately 6,000 residents (Programa Estado de la Nación, 2008). Since then, multiple instances of pesticide contamination in water sources near pineapple plantations were subject to hydrogeological investigations. These investigations, in parts, led to targeted measures to address the issue of drinking water pollution, such as in the Guácimo and Pococí areas, where two new aqueducts had to be built (Vargas-Castro, 2024). In addition, access to clean water remains a persistent issue in communities such as Santa Rita, Pital, Río Cuarto, and other areas of San Carlos, due to residual contamination from agrochemicals used in pineapple plantations, despite years of detection and subsequent prohibition (Muñoz Solano, 2022). In regard to the economic consequences of pesticide pollution in aquifers, Astorga Gättgens (2017) presented a calculation based on the scenario of establishing a pineapple plantation in Osa, where it is projected that the volume of contaminated water could reach approximately 45 million cubic meters. According to the authors, the expense of purifying this contaminated groundwater (around $500/m³) would surpass $20,000 million, a figure that would not be counterbalanced by the creation of two jobs per hectare, as proposed by this project. This also illustrates the adverse effect of current pineapple production on regional economic development efforts.

Regarding food product contamination, Artavia-Castro (2019) conducted a comprehensive analysis on pineapple safety assurance in Costa Rica, highlighting that preventing chemical residues on the fruit requires careful consideration of several critical factors. These factors include ensuring correct application methods, providing adequate training for personnel, precise equipment calibration, effective management of naturally occurring fruit conditions, and the implementation of stringent Good Agricultural Practices (GAPs) (Brenes-Alfaro et al., 2021). During the packaging phase, careful use of fungicides and food sanitizers is essential to maintain safety standards (Buitrago-Dueñas et al., 2018). Proper facility conditions, including sealed buildings and effective pest control, are very important in managing insect-related risks. Additionally, ensuring the integrity of materials, such as wood pallets,

is vital. These measures highlight the need for a holistic approach to pineapple food safety, incorporating formulation, application, personal training, equipment calibration, and adherence to agricultural best practices (FAO, 2007).

Societal response & options for more sustainable pineapple production

The expansion of the pineapple production in Costa Rica has triggered societal resistance (Chacón Soto, 2018). Acuña-Alvarado and Álvarez (2019) report disputes in communities near pineapple plantations in northern Costa Rica, which emerged from exploitative production practices affecting impoverished migrants unable to resist. This mirrors the national trend. The State of the Nation Report (2016) documents uncontrolled expansion of pineapple production and emphasizes its negative socio-environmental impacts as the plantation area increased over 23 times between 2004 and 2015. As Haberl et al. (2019) argue, this results in a scenario where the increasing use of biophysical resources, such as land, materials and energy, for pineapple production exceeds the natural capacity for regeneration. This excess triggers disturbances in ecosystems (e.g., biodiversity loss) and compromises the stability of society.

In addition to problems with competition for space and land conversion in the global biodiversity hotspot Costa Rica, the use of agrochemicals in the production process aggravates environmental and public health concerns. In 2018, researchers from the Center for Environmental Pollution Research (CICA) presented the findings of a study on the presence of agrochemicals in water sources. Samples were analyzed at 22 sites of surface water and 10 sites of groundwater since 2015, revealing contaminants such as Bromacil and Ametrina, commonly used in pineapple cultivation. Regarding Bromacil, the researchers asserted the absence of new traces post its prohibition in 2017, but did not confirm the current status of the contaminated water sources (Córdoba, 2018). Artavia-Castro (2019) argues for the necessity of improving governmental communication with all interested actors, especially with the producers and final clients, in order to work on prevention and not in a corrective way.

Activists have already sought international assistance to deal with the problem of agrochemical use in the pineapple industry. In 2015, individuals impacted by aquifer

pollution in Siquirres took their case to the Inter-American Commission on Human Rights (CIDH), based in Washington at the Organization of American States (OAS). Their aim was to prompt the government to adhere to Costa Rica's environmental laws and compel the alleged entity responsible for aquifer contamination, identified as the multinational pineapple production company Del Monte, to bear the financial and consequential burdens of their actions. Despite the commission ruling in favor of those who filed the complaint, it is crucial to emphasize that CIDH decisions do not have a binding nature on the country (Córdoba and Salazar, 2015).

In addition to the need for stricter regulations and stronger enforcement of existing environmental laws, knowledge of preventive measures to address the environmental and public health problems emanating from the agrochemical pollution is urgently needed. One of the very few studies demonstrating the usefulness of nature-based solutions for dealing with the implications of pesticides in the context of Costa Rican pineapple production was conducted by Echeverría et al. (2012) on the Río Jiménez watershed (Caribbean Coast). Using an experimental approach, the research revealed a positive correlation between the ecological health of aquatic macroinvertebrate communities and the condition of riparian vegetation and habitats, while an inverse relationship was observed with nutrient and pesticide concentrations. These results align with earlier research on temperate rivers, which also identified a close association between the quality of riparian habitat and forest, and that of aquatic ecosystems (Damásio et al., 2008, 2011). The studies show the importance of riparian vegetation to prevent environmental contamination by pesticides and reduce their public health impact by lowering chronic exposure.

Another factor that promotes sustainable pineapple production is biological pest control, mainly using fungal species. Applying this technology on a large scale allows companies to reduce the use of agrochemicals by up to 80%. In this way, the money companies used to buy agrochemicals can be invested in innovation and development, to manufacture their own bio-controllers. Aristoteles et al. (2011), for instance, also propose various approaches to reduce the reliance on pesticides, in pineapple cultivation, such as integrating predatory agents, rotating crops to manage soil pest populations, using cover crops to attract beneficial insects while supporting weed control and soil conservation, tracking pest and disease activity,

cultivating resistant plant varieties, and applying biopesticides. Adriano-Anaya et al. (2024) reported that strains of Bacillus subtilis and Rhizobium effectively served as biocontrol agents against Fusarium oxysporum wilt in pineapple, reducing the need for synthetic fungicides to manage the disease. Rodríguez-Rojas & Peraza-Padilla (2022) demonstrated the effectiveness of Beauveria bassiana in controlling Strymon megarus in pineapple cultivation fields.

It remains crucial to note that very little is known about the potential heavy metal pollution emanating from pineapple production (Samitha et al., 2021; Sodhi et al., 2018). Various heavy metals are extremely toxic and a highly perilous contaminant of water and soil (Mishra et al. 2019. Among other polluters, pesticides and fertilizer discharge is a significant source of metal contamination in the environment, which can partake in trophic transfer in food chains (Barakat, 2011). When they enter into living organisms, they bind with proteins, enzymes, as well as DNA molecules and form highly stable bio-toxic compounds, thus altering their proper functioning and obstructing them from the bioreactions (Mishra et al. 2018). Vargas-Camareno and Ledezma-Espinoza (2009) warn in this regard that Costa Rica faces a significant challenge of hazardous waste containing heavy metals. In the context of pineapple production, the solidification and stabilization technique, utilizing specific lignin-rich agro-industrial biomass residues, may be a promising treatment strategy. This approach not only addresses the hazardous waste issue but also holds the potential to impart added value to agro-industrial residues. Yet, given the implications of heavy metal contamination for the environment and human health, timely research specifically addressing the use of heavy metals in the pineapple production industry, its environmental impacts and public health implications are imperative.

The effect of pineapple stubble-added cement, in fact, demonstrated noteworthy immobilization of heavy metals under similar conditions (Vargas-Camareno & Ledezma-Espinoza, 2009). This finding underscores the viability of utilizing pineapple stubble in cement-based immobilization processes, providing insights into alternative and efficient waste management practices. The exploration of such techniques contributes to both environmental sustainability and the economic optimization of agro-industrial byproducts.

While the consulted literature emphasizes the responsibility of the private sector and the limitations in enforcing environmental laws, it is also necessary to recognize that phenomena such as diffuse pollution present significant technical and legal challenges. These issues do not necessarily result from a lack of governmental will, but rather from the difficulty in tracing direct responsibilities, applying sanctions, and operating with limited human and technical resources in public administration. Therefore, any strategy to improve the sector's sustainability must also consider these structural limitations that constrain the State's ability to act. International concern has also been raised. The United Nations has warned Costa Rica about its pesticide use and the associated health and environmental implications (Fernández, 2022).

Conclusion

This review provides an introductory overview of the environmental, societal, and health impacts associated with the intensified use of pesticides and fertilizers in pineapple farming, including possible chemical pollution of aquifers, threats to residents' health, and reduction in biodiversity due to the expansion of pineapple farming. In different regions of Costa Rica, economic policies aimed at increasing non-traditional exports since 1990 have led to a significant growth in pineapple cultivation. This expansion relies on the intensive use of pesticides to ensure high levels of product quantity and quality. Yet, the proliferation of pineapple plantations has established a challenging relationship with nature due to the release of chemical residues through agricultural metabolic processes. This process involves the release of chemical residues that may impact the environment, resulting in reduced, and even the loss of access to potable water for local communities, causing health issues.

The findings underscore the importance of adopting measures to mitigate environmental and health risks associated with the economically crucial pineapple industry based on a sound understanding of the complex dynamics between agricultural practices, environmental sustainability, and public health. However, current regulations, inadequate law enforcement, as well as delayed judicial rulings in Costa Rica lead to unresolved societal conflicts. The persistence of these conflicts is

particularly linked to the justified perception of pineapple plantations as a health risk by the local populations. A potential solution could be achieved if the government or businesses embrace more sustainable pineapple production practices, but given the economic significance of the pineapple industry, this seems unlikely in the short term.

This review also reveals that there is insufficient systematic data and knowledge on the type and amount of chemical substances used along the pineapple production chain in Costa Rica. This critical gap has to be urgently addressed in the near future. While there is at least some empirical evidence on the type of pesticides used, there is almost no knowledge about the pineapple industry's heavy metal pollution. More research is thus needed to better understand the complex dynamics between the chemicals used in the country's pineapple production chain, environmental contamination, and human health.

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