Literature Review on Residue Management of Sugarcane in Brazil and its Effects on Biodiversity

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Plain language summary

The use of agricultural leftovers, such as sugarcane residue, to produce bioenergy is currently gaining popularity. Something that was previously considered a waste product becomes part of a circular economy, reducing greenhouse gas emissions and potentially leading to sustainable energy production. Due to changes in harvesting from burning sugarcane residue to leaving them on the field, residue management is changing. This change in residue management and its potential to contribute to bioenergy make it an important research topic. The focus of this review is to investigate whether and how residue management influences biodiversity. Ensuring biodiversity is an important aspect of sustainable energy production and therefore worth investigating, especially to highlight where additional research is needed and what is already known.

Therefore, in this review, the following main research questions will be addressed:

How is biodiversity influenced by the residue management of sugarcane in Brazil?

To explore this, we conducted literature research focusing on the keywords "Brazil", "sugarcane", "biodiversity", and "straw removal". We analysed information from various papers, looking at the mentioned taxonomic groups, geographic regions (mainly Brazil), measurable effects on biodiversity, and different rates of residue removal.

We found that biodiversity generally increased when a certain amount of residue was left on the field. Specific taxonomic groups, such as soil microbes, nematodes and arthropods, were identified as being particularly impacted by changes in residue management. Even though the impact was mainly positive, meaning an increase in species abundance and diversity when the residue was left on the field, there are also certain pest species which benefit from the residue. This could lead to changes in pesticide usage, which in turn will impact the soil microbes, nematodes and arthropods. There was limited to no information available on the effects of residue management on other groups, like birds and mammals. Overall, we determined that biodiversity is indeed influenced by residue management strategies.

These findings underscore the importance of conducting further research on residue management and its implications for biodiversity. Considering biodiversity when working towards sustainable bioenergy production is seen as crucial. This suggests that more studies are needed to fully understand the potential impacts of residue management on biodiversity to develop effective and sustainable practices.

In conclusion, the use of agricultural residue for bioenergy production is gaining popularity, but it is important to consider the potential effects on biodiversity. Through literature research, it was found that residue management can impact biodiversity, with certain taxonomic groups being more affected than others. More research is needed to fully understand these impacts and develop sustainable practices that balance the need for bioenergy production with the conservation of biodiversity. This review highlights the importance of considering biodiversity in discussions surrounding agricultural residue management for bioenergy production to ensure a more sustainable approach.

Abstract

In an effort to lower greenhouse gas emissions, there is now increasing interest in producing bioenergy from agricultural residue, such as sugarcane residue. This shift in residue management strategies may have an impact on biodiversity, which remains to be investigated. Once the impacts are understood, measures can be implemented to minimise negative effects and preserve biodiversity, ultimately promoting sustainable bioenergy production. Therefore, literature research was conducted. Information from different papers was extracted based on the scope (Brazil) and the residue management impact of sugarcane on biodiversity. Certain mechanisms of impact were found. The decomposition of residue on the field helps fertilise the soil, reducing the need for artificial fertiliser. Additionally, herbicide usage may be impacted by the presence of residue, affecting the germination and growth of weeds and ultimately altering their composition. Moreover, soil compaction and soil pollution through leaching as well as the physical presence of residue affect biodiversity. Biodiversity was generally increased when there was a certain amount of residue left on the field. Specific taxonomic groups were identified that are affected by changes in the residue management. Mostly soil microbes and arthropods are studied, while there is a lack of available literature for other taxonomic groups such as mammals and limited literature for nematodes and birds. Overall, it can be concluded that biodiversity is affected based on residue management strategies. This review highlights the need for further studies concerning residue management and its effect on biodiversity. Including biodiversity when aiming at a sustainable production of bioenergy is relevant.

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1. Introduction

Currently, there is a shift from fossil fuels to bioenergy mainly to reduce greenhouse gas emissions (Cherubin et al. 2021). Bioenergy is a form of renewable energy, which aims to lead to a sustainable energy production in the future (Adami et al. 2012; Energy.gov 2024). The use of biomaterial (e.g. sugarcane) to produce bioenergy contributes to a bio-based economy. One approach is to use biomaterial residue to produce bioenergy. In general, residue is a byproduct obtained during the development of food crops (Guddaraddi et al. 2023). Using them for bioenergy production reduces waste and helps move towards a circular economy (Cherubin et al. 2021), which can be beneficial for humans as well as for the environment. Nevertheless, using biomaterial to produce energy can have negative effects on food security. The used fields compete for land and water with food production (Bordonal et al. 2018). Further, the increased use of biomaterials for energy production can cause pollution, the spread of certain diseases, and alter community composition and biodiversity (Verdade et al. 2015).

One biomaterial that is used to produce bioenergy is sugarcane residue, also known as sugarcane straw or trash. Sugarcane is one of the key crops used to produce bioenergy (Cherubin et al. 2019). It is therefore a useful example to get information about biomaterial used in bioenergy production. Using sugarcane residue to produce bioenergy can result in multiple social and environmental benefits. For example, it can reduce the environmental impacts of improper disposal of agricultural waste (Sindhu et al. 2016). The farmers would be able to generate an additional income when selling the residue instead of having to dispose of it. Further, it would help to generate jobs in rural areas, thus strengthening economic growth (Brazilian NR 2010). However, compared to other bioenergy sources like corn stover or switchgrass, sugarcane residue has a lower energy density. This implies that more sugarcane residue must be used to produce the same amount of energy, which can be more costly and difficult to handle logistically (Lu et al. 2016).

The harvesting strategy of sugarcane determines the residue availability. There are generally two sugarcane harvesting methods: manual and mechanical harvesting. Previously, the sugarcane residue was mostly burnt as part of manual harvesting (Carvalho et al. 2017). After the fields were burnt, the sugarcane was harvested. It is the fastest harvesting method and does not require expensive cutting machines. No residue is left after the burning. Another form of manual harvest is leaving out the burning and directly harvest the green cane. This is more labour-intensive but does not involve the destruction of residue. There are some semi-mechanised methods, which use mechanical grab for the burnt or green cane loading (Pongpat et al. 2017). Another method that is becoming more prominent is mechanical harvesting, which uses machinery. Now, more and more farmers move towards green cane harvesting, which does not include burning the sugarcane residue. Rather, the sugarcane residue is a waste product, which is either left on the field or can be used to produce bioenergy (Bordonal et al. 2018). The change from burning sugarcane to mechanical harvesting might have influenced biodiversity. Residue management may have an effect on biodiversity by altering the system and thus the conditions different plants and animals face. Ensuring that there is no or positive change in biodiversity when using sugarcane residue for energy production is important when aiming at sustainable bioenergy production. There are different ways to quantify biodiversity e.g. species abundance, richness and diversity (Menandro et al. 2019; Souza et al. 2010; Semie et al. 2019). Which tool or indicator works best is context specific. Variation in the abundance of species can have an effect on the local variation in biodiversity (Blowes et al. 2022).

Brazil is the world's largest sugarcane producer (Cherubin et al. 2021) and therefore, most relevant to focus on when investigating sugarcane. It is therefore a sensible choice to focus on sugarcane in Brazil when studying residue management for bioenergy production. There is already knowledge on the effects the expansion of sugarcane and land use changes can have on biodiversity. Certain species threaten to go extinct due to habitat destruction that results from changing native vegetation to agricultural land (e.g. sugarcane fields) or changing from one agricultural practice to another (Andrade et al. 2020; Adami et al. 2012; Duden et al. 2020). There is, however, a lack of extensive studies focusing on changes in residue management and their effect on biodiversity. Different forms of residue management (e.g. leaving residue or remove it) lead to changes in the local environment and the habitats it provides. Therefore, changes in biodiversity can be expected. There are regulations in place to reduce negative impacts on the environment and biodiversity, and ensure sustainable agricultural approaches (Frickmann Young 2013). They are an important legal framework to ensure commitment to best practices in residue management, which will ultimately improve or maintain biodiversity.

In this literature review, the scattered information about residue management will be gathered to gain new information and knowledge. The aim is to close the current knowledge gap and have a better understanding of the influence of residue management on biodiversity. Only once we understand the influence and the different effects of residue management on biodiversity, we can start to aim at reducing negative effects and opt for sustainable approaches of bioenergy production with regard to biodiversity.

To achieve this, the following main research questions will be answered:

How is biodiversity influenced by the residue management of sugarcane in Brazil?

To answer the main question, two sub-questions will be discussed:

- **Which mechanisms and types of effects are involved when studying biodiversity regarding residue management?**
- **Which residue management has which effects (positive, negative or neutral)?**

By answering these questions, potential threats to ecosystems and species can be identified, and the effects of current residue management strategies can be assessed. This information can be used to inform policy decisions and management strategies aimed at reducing negative impacts on biodiversity and preserving ecosystem health.

To tackle these research questions, literature research is performed. Different mechanisms through which residue management can influence biodiversity will be discussed. From this, we will zoom into the changes in different taxonomic groups. Then, some information about the limitations of the study as well as a short overview of some important policies and agreements concerning sugarcane cultivation and residue management will be presented. In the final section, the research questions will be answered, certain recommendations for farming strategies will be given, and further study ideas will be stated.

2. Methods

Literature research was performed with a focus on sugarcane in Brazil. Papers were searched in Google Scholar based on (different combinations of) the keywords “Brazil”, “sugarcane”, “biodiversity” and “straw removal”. Some papers from other countries were also included to be able to compare them to the residue management outcomes in Brazil. A targeted literature search was performed for these other countries based on countries mentioned in papers about sugarcane in Brazil.

The papers were first selected based on the title. The title had to include most of the relevant keywords or provide specific information that was lacking in other papers. The keyword “sugarcane” had to be included in all papers. From the selected papers, the abstracts and conclusions were read, and if they sounded relevant regarding the research question, the whole paper was read and included in the literature review. Papers focusing on quantitative as well as qualitative impacts were included.

The collected information from the papers included information on the geographic region as well as the taxonomic groups mentioned and the direction of impact. The direction can either be negative (reduced diversity due to residue removal), positive (increased diversity due to residue removal), neutral (no effect found), or both positive and negative depending on the intensity of the residue management, or more precisely, the amount of residue removed or left on the field. The method that was used to obtain the data and the measurement they used to determine biodiversity were also extracted.

3. Results and Discussion

3.1 Overview of found literature

The gathered information is summarised in Table 1 (see Appendix). Here, only papers are included that mention which specific taxonomic groups are changing and the direction of the impact. Papers that only mention that there is a general biodiversity loss are excluded from the table. The impacts were studied in more detail in Sections 3.2 and 3.3 and are only summarised in the table. There is only a limited amount of literature available concerning the residue management of sugarcane in Brazil.

There were two types of methods identified for Brazil: Papers about experiments that were performed investigating the effects of residue management on specific taxonomic groups (see Table 1 and 2) and literature reviews (Bordonal et al. 2018; Carvalho et al. 2017; Dinardo-Miranda and Fracasso 2013; Verdade et al. 2015). As seen in Table 2, most papers focus on sugarcane residue management in Brazil. There were also some papers where research was performed in other countries, such as Australia, China, Pakistan or India. The main focus of the papers was on soil microbes and on some arthropods, with limited literature available for nematodes. Papers looking at other taxonomic groups (e.g. mammals) were lacking. Literature on the effects of residue on plant species (excluding the sugarcane plant) is limited to indirect effects based on weed control (Adami et al. 2012; Da Silva et al. 2018). Most papers based their conclusions on fieldwork, which was sometimes extended with labwork to identify the samples. Biodiversity was measured as species richness, abundance or diversity. Figure 1 is a visual overview of the mechanisms and effects found in the different papers. The presented mechanisms are explained in Section 3.2, and the effects on the different taxonomic groups are discussed in Section 3.3.

Table 2: Summary of Table 1 with the exact number of papers found per category.

Country	Taxonomic group	Impact	Method used	Biodiversity measure
Australia = 1 Brazil = 8 China = 1 India = 1 Pakistan = 1	Soil microbes = 9 Nematodes = 2 Arthropods = 4	Negative = 5 Positive and negative = 4 Negative and neutral = 3	Fieldwork = 5 Fieldwork and labwork = 6	Richness = 3 Abundance = 9 Diversity = 5

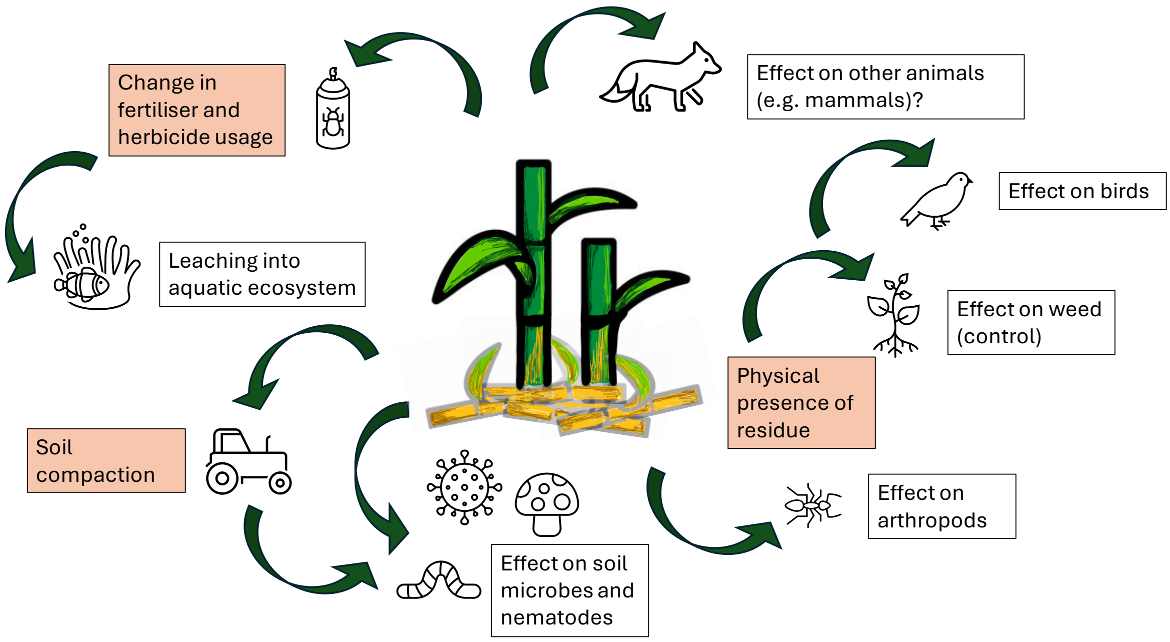

Figure 1: Summary of the mechanisms and effects sugarcane residue has on biodiversity. The orange boxes represent the mechanisms and the other boxes the effects they have on specific taxonomic groups. The arrows show the relationships between mechanisms and effects.

3.2 Mechanisms through which residue management influences biodiversity

Changes in harvesting strategies and residue management

Different studies found that soil microbial diversity depends on the harvesting strategy (Rachid et al. 2013; Wallis et al. 2010). Sugarcane burning reduces the amount of available carbon, therefore possibly reducing the growth of microbes (Wallis et al. 2010). Leaving residue on the field rather than burning it increases the biomass of macrofauna and earthworms, in particular. They have an important role in carbon enrichment and therefore potentially influence the soil carbon pool (Razafimbelo et al. 2006). In the past, burning was the most commonly used harvesting strategy (Aguiar et al. 2011). Therefore, the soil and in general microbial diversity might still have to recover from this. Because of this, it is sometimes hard to evaluate whether leaving residue influences biodiversity or whether it is rather the lack of burning. There are three options when it comes to handling the residue: burning them, leaving them on the field, or (partially) removing them. Which residue management strategy is used depends on the harvesting strategy. Since sugarcane harvesting is moving towards green cane harvesting, the effects of sugarcane burning are less extensively discussed in this review.

Physical presence of residue

The presence of residue on the field can affect the germination, dormancy and mortality of certain weed seeds and therefore impact the composition of the weed community. Certain weeds are inhibited in their growth, while others benefit from the conditions provided by the residue (Carvalho et al. 2017). The general decrease in the efficiency of weed control increases the abundance of certain birds (Verdade et al. 2012). The different agricultural stages of the sugarcane do not influence the richness or abundance of bird species (Penteado et al. 2014). This could mean that the actual condition of the sugarcane field plays only a minor role when it comes to the diversity of bird species. The surroundings of the field and the farming techniques of adjacent fields might be more important. Nevertheless, leaving residue on the field might provide habitat for certain species, leading to a sort of domino effect on other species. Also, leaving residue on the field reduces variability in soil temperature and retains moisture due to less direct solar radiation on the soil (Menandro et al. 2019). This changes the environmental conditions that species face.

Fertiliser and herbicide usage

If the sugarcane residue is left on the field, then less fertiliser is needed since the residue itself acts as a fertiliser (Cherubin et al. 2019). This would lead to fewer changes in soil composition and less pollution of water through artificial fertilisers. In a review by Bordonal et al. (2018), the authors show that efficient recycling of nitrogen (N) fertiliser might be expected in the future and that the amount of fertiliser can be reduced after some time when having residue on the field. Part of the nitrogen becomes immobile due to microorganisms. Nevertheless, sugarcane residue is an important source to sustain the nitrogen stock in the soil (Cherubin et al. 2019). Leaching of nitrogen is considered a minor problem (Filoso et al. 2015). Phosphorus (P) is another macronutrient that can be received from decomposing residue. The residue left on the field can lead to higher diversity and activity of certain microorganisms that are capable of converting organic phosphorus to a soluble form that is available to plants as well as to mycorrhizal fungi (Cherubin et al. 2019). Potassium (K) can also be gained from sugarcane residue. Less potassium fertiliser is used when leaving the residue on the field. Additionally, potassium from the residue is released slower than the potassium from fertilisers therefore leading to less potassium. Total residue removal may lead to double the amount of NPK-fertiliser used for sugarcane fields in the next 25 years (Cherubin et al. 2019). So, even though fewer fertiliser is used when leaving the residue on the field, the residue increases the occurrence of macropores in the soil and therefore increase the risk of leaching (Pankhurst 2006). This might affect soil microbes and aquatic ecosystems negatively (Filoso et al. 2015).

Additionally, if there is more residue on the fields, there is a higher herbicide runoff into the water for herbicides with a high water solubility (Trovato et al. 2020). This runoff might then affect plants close to the sugarcane fields. Regardless of the amount of residue on the field, a certain amount of herbicide can always reach the ground. The residue can act as a physical barrier, which obscures the herbicide from reaching the ground and therefore weed control becomes less effective (Da Silva et al. 2018). This would mean that to reduce the same amount of weed, more herbicide is needed, which then would also increase the amount of herbicide in the runoff water and thus have negative impacts also beyond the sugarcane fields.

Soil properties

The current land use changes (LUCs) influence soil properties such as its porosity, chemical quality and soil carbon stock, which impacts soil macrofauna diversity (Cherubin et al. 2021). The use of heavy machinery in sugarcane fields compacts the soil and destroys habitats for soil microbes (Cherubin et al. 2016). Considering that mechanical harvesting of green cane needs more heavy machinery compared to burning as part of the harvesting strategy, we might expect higher soil compaction, which might negatively impact biodiversity. Additionally, total removal of residue increases soil compaction (Menandro et al. 2019). Removing sugarcane residue may also mean that heavy machinery has to be used to collect part of the residue. Soil tillage can reduce soil compaction in the short-term, but in the long-term it increases the risk of erosion and structural degradation (Cherubin et al. 2016). Therefore, soil compaction should be minimised to avoid negative impacts on soil and biodiversity.

3.3 Effects on taxonomic groups

Soil microbes

The amount of residue that is left on the field seems to be important when evaluating effects on biodiversity. Total removal of residue has negative impacts on the abundance of soil microbes (Morais et al. 2019; Suleiman et al. 2018). Also, the composition of the soil microbe community changes depending on the residue management. In a short-term experiment performed by Rachid et al. (2016), a difference in the community composition of fungi depending on the amount of sugarcane residue on the field could be found. This is confirmed by Morais et al. (2019) who found reduction in the fungi abundance when all the residue was removed from the field. Fungi are very efficient at breaking down long and complex carbon chains, as are present in sugarcane. Fungi can therefore break down sugarcane and use it for their own growth (Rachid et al. 2016). When comparing these results from Brazil with results found in other countries, they largely match. A study performed in India for example found a positive influence on arbuscular mycorrhizal fungi (AMF) when residue was left on the field (Surendran et al. 2016). Another study performed in China found a higher diversity in the fungal community when the residue was left on the field while reducing soil-borne pathogens (Zhang et al. 2021). A study performed in Australia found a predatory fungus, which was only present in soil covered with residue (Stirling et al. 2005). This concludes that sugarcane residue seems to have a positive influence on fungal diversity.

Residue also influences bacteria. The bacterial abundance was reduced when removing all the residue (Pimentel et al. 2019). This study was performed over a longer period and found an increase in the abundance of specialists when all the residue was removed. Importantly, they highlight that the composition of the residue is what determines the effects it has on the bacteria and ultimately which bacteria are how abundance. Moderate residue removal had no negative effect on the bacteria. However, another study found no effect on the bacterial community independent of the amount of residue on the field (Rachid et al. 2016). Since it was only a short-term experiment, there might have been a reduction in abundance, which was not captured, and maybe a decrease in diversity in the long term.

The ideal amount of residue left on the field is at least 7 Mg ha^-1 of dry residue to ensure agronomic benefits (Carvalho et al. 2017). A residue removal of around 50% is said to result in the highest diversity of microbes (Pimentel et al. 2019). However, this number has to be used carefully, since the effect is soil and rainfall and therefore location specific (Carvalho et al. 2017). Changes in conditions caused by the physical presence of residue on the soil also influence microbe community composition.

Nematodes

Dinardo-Miranda and Fracasso (2013) did not observe any effects of residue on nematode. However, when considering the effect of residue on nematodes in Australia, Stirling et al. (2005) found some effects. They found that having residue on the field increases the number of bacterial-feeding nematodes, while also increasing the population of bacteria and fungi. The number of plant parasitic nematodes was decreased. Comparing the findings from Brazil and Australia emphasises that not all nematodes behave the same, but also that there is still a knowledge gap when it comes to the diversity of nematodes but also on the further effects potential changes in their abundance might have on soil microbes.

Arthropods

When looking at ant species, more generalists were found when the residue was left on the field (Souza et al. 2010). Even though generally the ant diversity increased when the residue was left on the field, some ant species decreased in abundance, possibly due to unfavourable conditions and competition with other species. Certain ants are used as pest control (Souza et al. 2010). This would mean that leaving residue on the field has also a direct positive effect on the sugarcane plant itself, and therefore also positive effects on the yield and economic benefits for the farmers. The exact amount of sugarcane necessary to ensure the positive effect would have to be tested. Potentially, one could remove part of the residue for bioenergy production and still ensure ant biodiversity. The control of leaf-cutter ants might become less efficient because the residue on the field makes it harder to find their nests (Dinardo-Miranda and Fracasso 2013). It will have to be a balancing of the positive and negative effects to find the best management strategy regarding ant diversity and abundance.

Other arthropods have been studied concerning residue management, too. The root spittlebug for example increased in abundance because the residue increases soil moisture, which favours root spittlebugs. They have now become a pest for the sugarcane plant. It might be sufficient to remove part of the residue and leave some on the field without having negative effects (Dinardo-Miranda and Fracasso 2013). The effects of residue removal could be seen stronger in clayey soil compared to sandy soil (Castro et al. 2019). Another pest that is benefiting from residue on the field is the sugarcane weevil. The residue acts as a shelter and might therefore have a positive effect on the population abundance (Dinardo-Miranda and Fracasso 2013). Castro et al. (2019) found that removing residue does not influence the abundance of the sugarcane weevil but reduces the damage done to the sugarcane plant. They also concluded that residue removal is not a sufficient strategy to control the damage done by the root spittlebug and the sugarcane weevil. The sugarcane borer, which is another pest, is also more abundant now that burning is no longer used (Dinardo-Miranda and Fracasso 2013). Whether this is because of the residue or the lack of burning remains to be investigated. Some small increases in abundance due to the residue are however expected (Dinardo-Miranda and Fracasso 2013). Pest control of the giant sugarcane borer might be complicated by the residue on the field. The pest is currently controlled by the collection and removal of caterpillars and pupae. Finding them in the residue is more difficult (Dinardo-Miranda and Fracasso 2013). In general, it can be said that residue on the fields can lead to an increased abundance of certain pest species, which in turn requires more pesticides. The use of pesticides can have negative effects on animal health (Schiesari and Grillitsch 2011), which could then decrease animal abundance and ultimately lead to reduced biodiversity.

A study performed in Pakistan found that better management strategies including leaving residue on the field improves the diversity of certain arthropods (Sajjad et al. 2016). Another study from Pakistan looked at the food chain. They found that negative effects on arthropods can have effects on the whole food chain including birds, amphibians and reptiles (Sajjad et al. 2012). Even though no corresponding study could be found for Brazil, similar effects can be expected. Disruption of one taxonomic group in a food chain can have effects on other species through trophic interactions (Thébault and Loreau 2006) thus potentially influencing biodiversity.

3.4 Limitations

One major limitation is the limited amount of research done concerning the biodiversity impact of sugarcane residue management. Also, the available literature is skewed with a focus on soil microbes, nematodes and arthropods. Even within these three groups, the availability and depth of the literature differ. While for arthropods specific species are investigated, for soil microbes the available information is often quite general. Pest species seem to be studied more extensively possibly also due to the economic interest in their reduction and management. Only very limited literature was available for nematodes.

Further, there is a lack of literature focusing on larger animals such as mammals. Even though larger animals can travel larger distances and have bigger home ranges (Gheler-Costa et al. 2012), their presence has an influence on the whole food chain and on smaller animals. Also, there might be a lack of literature because there is no effect present in larger animals or because they were not studied extensively. Additionally, studying larger animals might be of less importance since they might not directly influence the sugarcane plants and are therefore of less economic interest.

Also, the majority of papers investigate residue management in Brazil, which leads to a limited geographical scope and spatial diversity. Another problem is that the switch from burning to green cane harvesting is still ongoing. This means that there are still some long-terms effects from the burning visible in green cane harvested fields, which makes differentiating of effects more difficult. The effects can be because of no more burning or because of the implemented residue management. Additionally, this review focuses only on biodiversity, which is one aspect of sustainability. To get a better understanding of sustainable approaches and management strategies, a more extensive literature research would be needed. This would allow adaptions and improvements to current residue management policies.

3.5 Policy and regulatory framework

Understanding the current regulatory framework concerning residue management helps to determine weaknesses and room for improvement, considering the current knowledge on the effects on biodiversity. It determines how the information about residue management obtained in research is actually used and implemented in policies. In Brazil for example, there is a land use policy in place, which defines the expansion of sugarcane fields, called “Sugarcane Agroecological Zoning”, short AGZ. This document aims to regulate expansion and sustainable production of sugarcane (Manzatto et al. 2009). This is already an important step towards safekeeping current biodiversity and avoiding destruction and reduction of habitat. Changes in the habitat can lead to severe effects when it comes to species diversity. Sugarcane expansion led for example to a higher abundance of capybara, which play an important role in Brazilian spotted fever (Barros Ferraz et al. 2007; Labruna 2013). The overall dynamic of rodents changes, which are on one side prey for certain predators and on the other side reservoirs for certain diseases (Gheler-Costa et al. 2012; Labruna 2013; Verdade et al. 2011). This emphasises the importance of having regulations concerning the expansion of sugarcane. In 1995, the Green Protocol, a voluntary agreement, was signed by the government of the State of São Paulo, Brazil’s top sugarcane-producing state, and UNICA’s associated mills to end burning sugarcane as part of the harvesting process (SugarCane.org 2021) and to move towards sustainable approaches (Frickmann Young 2013). Another organisation, which includes different actors involved in the sugarcane production chain (e.g. farmers, millers, traders, buyers and certain organisations) is Bonsucro. It focuses on sustainable sugarcane production, reduction of greenhouse gas emissions and reduction of water usage (Bonsucro 2024). These are all important policies when it comes to the sugarcane sector as a whole. Understanding these shows that the sugarcane sector is moving towards more sustainable solutions.

When it comes to regulations specifically related to residue management of sugarcane cultivation, they are mentioned in the National Policy on Solid Waste (NPSW) (Brazilian NR 2010). There it is mentioned that “recyclable and reusable solid waste” should be considered as an economic asset. Further, environmental quality should be protected, and waste should be reduced, reused or recycled if possible. This should ultimately lead to a circular economy regarding solid waste management. Mancini et al. (2021) discuss in their paper the challenges and opportunities faced by Brazil when aiming at a circular economy. Logistics as well as research could be improved to guarantee a circular economy, which benefits everyone. Additional focus should be set on reducing pesticide usage through controlled and local usage or the development of resistant crops. It would be important to further inform the farmers about the possible waste management practices and the resulting benefits. Better logistics within the country would facilitate a circular economy and benefit farmers, energy producers, energy users and ultimately the environment and its biodiversity.

4. Conclusion

Removal of residue can influence biodiversity through several mechanisms. The physical presence of the residue affects the weed community and the usage of fertilisers and herbicides changes. The soil changes as well through processes such as soil compaction. The observed effects on biodiversity of leaving sugarcane residue on the field compared to removing them were mostly positive. For soil microbes, leaving at least a certain amount of residue on the field has a positive influence (Morais et al. 2019; Suleiman et al. 2018; Menandro et al. 2019). Also, the diversity of ant species increased when there was residue present (Souza et al. 2010). Additionally, the abundance of certain pest species increased (Dinardo-Miranda and Fracasso 2013). The effects on nematodes are not clear since positive, negative and neutral effects were observed (Dinardo-Miranda and Fracasso 2013; Stirling et al. 2005). The different mechanisms and effects are summarised in Figure 1 (Section 3.1).

The current regulatory framework shows that the sugarcane sector is aiming to reach sustainable solutions, which will aid to safeguard biodiversity. There are certain steps that can be taken to avoid or minimise bad effects that might occur when removing residue from the fields. Some of these would solve some of the mentioned problems, while others try a different approach. A first step would be to only remove part of the residue, which would not reduce the beneficial effects of residue on biodiversity and still allow part of the residue to be used for bioenergy production (Cherubin et al. 2016). Another step would be to implement precision farming techniques. Using sensors, GPS, and data analytics, this method precisely customises inputs to meet the requirements of individual plants or crops. This would reduce the unnecessary use of pesticides as well as optimise the use of land by allowing simultaneous cultivation of food crops and crops for bioenergy production (Soyombo et al. 2024). It would also allow to assess the optimal amount of residue on the field to reduce any excessive fertiliser usage. Agroforestry could also improve biodiversity through the simultaneous cultivation of trees, food and bioenergy crops (Soyombo et al. 2024). This would increase the diversity of the landscape and ultimately lead to a higher niche availability and therefore to an increased biodiversity by reducing monoculture and enhancing a more diverse flora and fauna. Even though this is not directly linked to residue management, it would allow animals to use the newly created habitats and therefore compensate for any potential habitat loss due to the removal of residue. By implementing one of these strategies, biodiversity might be increased, and possibly a greater part of the residue can be used to produce bioenergy with limited negative impacts. This would however have to be tested in a future study. Especially since the actual amount of residue necessary to reach the maximal biodiversity is site-specific (Carvalho et al. 2017). Therefore, further investigation of the different factors that play a role such as soil composition, rainfall, or temperature will allow a more detailed calculation of the necessary amount of residue on the field to maintain or increase biodiversity. Further studies should be performed on a larger scale and over a longer period of time including soil microbiota as well as plants, animals and aquatic systems. This would allow us to determine the effects of residue more precisely and would also ensure that using a certain amount of residue to produce bioenergy is a sustainable approach regarding biodiversity.

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6. Appendix

Table 1: Summary of the papers that mention specific taxonomic groups and their effects.

Reference	Country	Taxonomic groups	Impact of residue removal	Method used	Biodiversity measure
(Castro et al. 2019)	Brazil	Arthropods (pests)	Negative and neutral	Fieldwork	Abundance
(Dinardo-Miranda and Fracasso 2013)	Brazil	Soil microbes, nematodes and arthropods (pests)	Negative and neutral	Review	-
(Menandro et al. 2019)	Brazil	Soil microbes	Negative	Fieldwork	Abundance, richness, diversity (Shannon's index)
(Morais et al. 2019)	Brazil	Soil microbes	Negative	Fieldwork and labwork	Abundance
(Pimentel et al. 2019)	Brazil	Soil microbes	Negative and positive	Fieldwork and labwork	Abundance
(Rachid et al. 2016)	Brazil	Soil microbes	Negative and neutral	Fieldwork and labwork	Abundance
(Sajjad et al. 2016)	Pakistan	Arthropods	Negative	Fieldwork	Abundance, richness and diversity (Shannon-Wiener index and Simpson Index)
(Souza et al. 2010)	Brazil	Arthropods	Negative and positive	Fieldwork	Abundance, richness and diversity (Shannon's indexes of biodiversity and evenness)
(Stirling et al. 2005)	Australia	Soil microbes, nematodes	Positive and negative	Fieldwork	Abundance
(Suleiman et al. 2018)	Brazil	Soil microbes	Negative	Fieldwork and labwork	Diversity (Shannon's and Simpson index)
(Surendran et al. 2016)	India	Soil microbes	Negative	Fieldwork and labwork	Abundance
(Zhang et al. 2021)	China	Soil microbes	Positive and negative	Fieldwork and labwork	Diversity (Shannon's index)