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Water, Waste, Energy and Food Nexus in Brazil: identifying a resource interlinkage research agenda through a systematic review

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Abstract

The resource nexus consists of a framework to address interlinkages between natural resources and systems that provide water, energy, food and waste management. It transcends traditional assessments conducted in "silos", raising trade-offs and synergies that are rarely acknowledged. The nexus framework is intrinsically context-specific, as each respective region has particularities in terms of critical interlinkages. Brazil is the world's eighth largest economy [1] and is heavily reliant on natural resources. This paper considers Brazil to be a textbook case for nexus research that identifies critical interlinkages that are neglected by literature, which is typically based on single-resource analysis. It proposes a research agenda to advance resource nexus assessments and improve resource governance in Brazil. We propose a novel method for nexus research, systematically reviewing geographical context-specific papers in relevant single nexus dimensions and establishing resource interlinkages that characterise research gaps and policy priorities. We found that 36% of practices reviewed involve more than one resource at a time, characterising interlinkages not analysed by the literature. Lastly, selected quantitative indicators were used to identify critical interlinkages by analysing the representativeness of practices in the national context, and the

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relevance of synergies or trade-offs for Brazil. Critical interlinkages in Brazil were found to be irrigation for energy crop expansion (water, food and energy); transport biofuels and fuelwood (water, energy, food); deforestation for new pasture (water, energy, food); and hydropower generation (water and energy). These are, therefore, priorities for future nexus research and for efforts to address synergies and trade-offs in resource governance.

Highlights:

The nexus framework assesses and emphasizes critical interlinkages across natural resources.

Critical interlinkages embedded in resource use practices were identified.

Interlinkages between water, waste, energy and food in resource use and management practices were identified.

A research agenda around resource interlinkages in Brazil was developed.

KEYWORDS: Water, Waste, Energy, Food, Nexus, Practices, Natural Resource Management, Interlinkages, Brazil

Word count: 9225 words.

List of abbreviations

ABiogas Brazilian Biogas Association

ANA National Water Agency

ANEEL National Electric Energy Agency

CNPE The National Council for Energy Policy

EMBRAPA Brazilian Agricultural Research Corporation

GPV Gross Production Value

GW Giga Watt

IBGE Brazilian Institute of Geography and Statistics

IPCC Intergovernmental Panel on Climate Change

PNAD National Household Sample Survey

SDGs Sustainable Development Goals

SIN National Interconnected System

1. Introduction

The resource nexus emerged in the context of the Rio+20 conference as a framework to assess interlinkages between natural resources and an integrated approach to improve their management and use. Recently, the resource nexus has gained momentum as a means to deliver the United Nations' 2030 Agenda for Sustainable Development [2–5]. According to Bleischwitz *et al*. [6], the resource nexus can be defined as a set of critical interlinkages among natural resources that are used as inputs for essential services to human life, such as water, energy and food, and their value chains. Natural resource scarcities and the recognition that resources are interlinked by complex relationships are at the core of nexus debates [7]. Thus, the resource nexus has recently gained significant interest as a potential means to effectively consider such interlinkages in resource use, governance and planning. The nexus framework is intrinsically context-specific, as each respective region will have their particularities in terms of critical interlinkages. Hence, nexus research should ideally be conducted downscaled to a country or regional focus.

Developing countries, such as Brazil, whose societies and economic activities rely heavily on natural resources, face particularly important trade-offs and synergies regarding resource interlinkages. It is argued that by adopting this integrated approach, they can improve policy options and benefit from increased resource efficiency [4,8].

However, being a new framework, the nexus is not yet embedded in resource use and management literature, which tends to analyse each resource separately. Therefore, the aim of this paper is to propose a research agenda for the resource nexus framework in Brazil, highlighting the most important interlinkages between two or more resources as research gaps. Nexus analysis is intrinsically context-specific. Being a large emerging economy, whose economic activities are based to a large extent on agriculture and renewable resources, Brazil will prove to be a blueprint for such efforts. Indeed, Mercure *et al.* introduce Brazil as a "textbook" nexus example [9].

Thus, particularly strong resource interlinkages emerge in Brazil, which has an area of over 8.5 million km^2, five geopolitical regions, a population of nearly 210 million people and five different climate zones [10]. As a resource-rich country of continental dimensions, whose exports are based on agricultural and energy commodities, relevant resource interlinkages emerge from the Brazilian economic sectors. Interlinkages between water and food, water and energy, and water, energy and food, emerge across activities producing relevant goods for food and energy security, for example. To date this is not reflected either in the literature or in resource governance, and may have relevant impacts over the Brazilian economy in both the short and long terms.

Despite the relevance of the resource nexus approach to analyse interlinkages in Brazil, it is still a novel concept and studies that have adopted this approach, either as a method or as an analytical framework, are scarce. Instead, literature is focused on single-resource analyses that rarely acknowledge the trade-offs and synergies between different resources.

When searching both Scopus and Web of Science, only nine papers focussing on Brazil and framed within the resource nexus can be found, meaning only nine case studies for Brazil use the word “nexus” at all [9,11–18]. These studies include: Mercure *et al.* [9] who describe four case studies of nexus interlinkages in Brazil ; Rodriguez *et al.* [19] who assess the potential for soybean biofuel crop expansion by analysing water footprints, water availability and land availability in Brazil [11]; Sobrosa *et al.* [14] who assess country-level sustainable options for water and energy use in beef-cattle ranching [14]; and, Bellezoni *et al.* [15] who apply a hybrid Input-Output framework to analyse water-energy-food interlinkages of sugarcane ethanol production in the state of Goiás.

This paper therefore undertakes a systematic review not only of articles which directly propose analyse the resource nexus, but al articles which water, waste, energy and food practices in order to identify interlinkages that can be the focus of future studies. Practices are defined as technological and organizational options adopted by populations and service providers to guarantee access to water, food, energy and to provide a destination for waste. Section 3.1 provides a full description of the concept used in the systematic review method.

This paper starts with the hypothesis that the current literature is mostly single resource-focused, thus neglecting trade-offs and synergies that resource governance should take into account. Papers framed within the resource nexus framework also tend to tackle only one trade-off or synergy at a time, not providing a macro-level picture for a country or region. By contrast, the method proposed here maps all relevant synergies and trade-offs embedded in resource interlinkages in Bazil, highlighting the critical nodes to be examined in future studies and governance efforts. The method therefore consists of screening available literature in relevant single nexus dimensions and identifying resource interlinkages in the Brazilian context. We assess the linkages involving two or more resources (i.e. water, food, energy and waste), looking at practices including upstream to downstream users. Finally, we identify critical interlinkages for Brazil by analysing the representativeness of practices in the national context, the relevance of synergies or trade-offs embedded in the interlinkage, and the gap in the literature regarding these critical nodes.

2. The resource nexus in Brazil – an overview

The nexus approach aims to integrate resource management and inform governance through identifying trade-offs across sectors and optimising their synergies [3]. It assesses and emphasizes critical linkages across resources as a response to the single-resource predominant mindset [30]. The persistence of a sectoral approach to resource governance leads to policy responses to resource constraints being conducted in isolation. This leads to segmented planning and decision-making frameworks, and to unintended consequences for other sectors and resources. Sharmina *et al.* [31] argue that the main aim of nexus thinking is to transcend traditional policy-making and modelling assessments which take place in “silos”, starting by overcoming potential conflicts and trade-offs sometimes not acknowledged even between the objectives of a single resource. The inadequate attention paid to interactions among resource systems has resulted in a failure to incorporate trade-offs and synergies, hindering development progress through livelihood insecurities and impeding sustainable development [7].

It is thus increasingly clear that the nexus provides a more valuable approach to frame an analysis on resource access and sustainability. The nexus has already gained wide support as a concept to create integrated solutions in research and resource governance, through identifying trade-offs across sectors and optimising their synergies [3].

However methods to perform assessments that properly incorporate interlinkages are still being developed. Most traditional methods of analysis have not been designed to capture and understand externalities generated by interactions between resources. This is reflected in the fact that most of the literature addresses scarcity and sustainability of one resource at a time, and does not consider trade-offs and synergies with other resources. Interdisciplinarity and stakeholder participation are therefore often cited as essential aspects to successfully create methods and support decision-making with multi-sector, integrated perspectives [31–34].

Developing countries face many challenges related to resource access and are more vulnerable to resource scarcity and governance failures, thus benefiting more from the improvements provided by a nexus approach. According to current demand and resource degradation projected trends, there is a need for agricultural production to grow 70% in developing countries from 2010 to 2050, as opposed to 27% in developed countries, considering climate change effects [35]. To achieve this, agricultural land area would need to grow 20% in developing countries, and 30% in Latin America specifically, in contrast with a 10% world average [36]. This would increase water demand, even accounting for efficiency gains led by technological progress; strategies to promote the use of biofuels would have a compounding effect. Thus, water, energy and food challenges should be faced in an integrated manner.

The impacts of climate change are projected to have the worst impacts on developing economies. For instance, according to the Intergovernmental Panel on Climate Change (IPCC) projections, the Brazilian North-East Semi-arid region is expected to be one of the world’s most impacted regions [37]. Evidence shows that short, medium and long-term total rainfall will decrease, temperatures will increase and there will be a rise in consecutive drought days, incidence of heat waves and water deficiency [38]. The IPCC has predicted that across South America, rainfall will vary geographically, most notably showing a reduction of 22% in North-East Brazil [37]. In North-East Brazil, these climate impacts will reduce the production of the most consumed agricultural staples, such as cassava and maize, by up to 10%, and rice and beans up to 30% [37].

Resource access and management practices are central in determining the relationships between populations and the natural environment. The integration of human and natural systems is critical to understand socioeconomic and environmental linkages and to elaborate sustainable resource access and management solutions [39]. Hence, a key objective of nexus research is to understand how human-environment systems relate to the environment and to processes of socioeconomic development in emerging economies, such as Brazil [4,39].

Table 1 shows critical access in rural areas for sewage systems and water and waste management in Brazil, as well as deficits in the provision of electricity and food.

Table 1. Resource access indicators in urban and rural Brazil

Resource access urban and rural Brazil 2015		
	Urban	**Rural**
Sanitation	**2015**	
Sewage system	67%	5%
Septic cesspit	21%	33%
Rudimentary cesspit	10%	44%
Open trench	1%	4%
Directly disposed in river or lake	1%	3%
Other	0%	1%
No sewage system	1%	11%
Solid waste	**2015**	
Collected (garbage)	98.8%	33.9%
Burnt or buried in the property	1.0%	62.0%
Disposed in wasteland	0.2%	3.4%
Disposed in river or lake	0.0%	0.1%
Other	0.0%	0.5%
Water provision	**2015**	
Internal piping - general network	93.5%	31.2%
Internal piping other	5.1%	46.4%

No internal piping - access to general network	0.4%	3.3%
No internal piping - no access to general network	0.9%	19.1%
Electricity	**2015**	
Connection	99.95%	98.25%
No connection	0.05%	1.75%
Food	**2009**	
Food security	67%	60%
Food insecurity (total)	33%	40%
Mild	21%	22%
Moderate	7%	10%
Severe	5%	8%

Source: Own elaboration with data from [40,41]

Small-scale or family farming remains widespread in Brazil. Their practices have been widely studied in the literature, which is analysed in detail here. The last agricultural census, conducted in 2006, showed that over 84% of agricultural properties in Brazil are family-based[1], although they occupy only 24.3% of total agricultural area. According to the Brazilian Ministry of Agriculture, 70% of all food goods gross production value in Brazil comes from family agriculture, which employs 74% of the national rural workforce [42,43].

The most important agricultural and livestock commodity in terms of production value in Brazil is soybeans (Figure 1), which is mostly used for animal feed, food-industry processing and biodiesel production. In 2018, 63.2% of total soybeans produced in Brazil were exported, mainly to China and the European Union [44]. Beef is the second commodity in cumulative production value as shown in Figure 1. The increasing demand of pasture for cattle and soybean plantation frontiers are known to cause deforestation in the Amazon and Cerrado (Brazilian Tropical Savannah) biomes, influencing rainfall regimes in the country [45–50], therefore revealing a critical water and food interlinkage.

[1] Family-based agricultural properties are defined by the law nº 11.326/2006 as rural properties where workforce employed is of members of the family, household income refers to the enterprise and it has a maximum certain size hectares, according to each municipality [238].

The water and food interlinkages in watering systems for animals also demand attention. The National Water Agency (ANA) [51] estimated that, in 2017, water consumption by animals was almost 4 billion m^3/year; equivalent to 10.8% of all water consumed in Brazil. This was higher than industry consumption (8.8%) and similar to total household consumption (11%) [51].

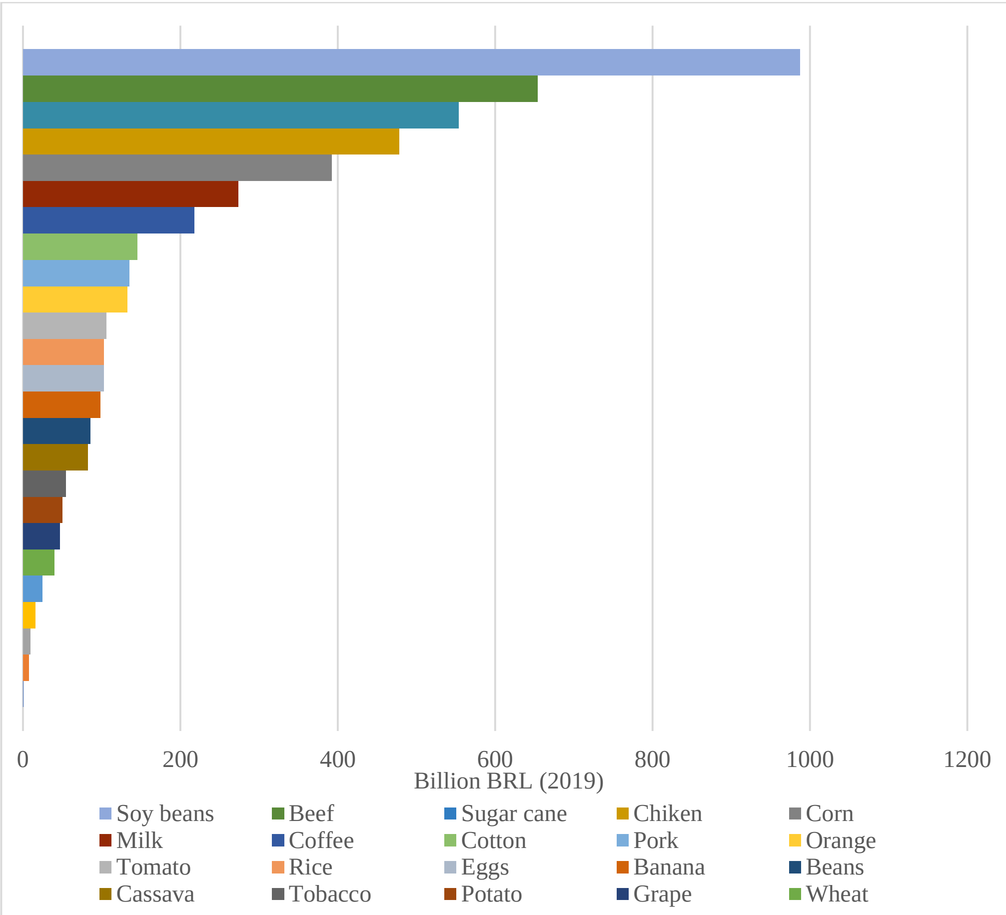

Figure 1. Brazil's Cumulative Gross Production Value (GPV) of agricultural and livestock goods 2010-2018 billion BRL (2019)

Source: own elaboration using data from [52]

Biofuels, including sugarcane ethanol and soybean biodiesel, reveal not only the best-known interlinkage between land/food and energy, but also water. Irrigation was the largest water consumer in Brazil, accounting for 68.4% of all water consumption in 2017 [51]. According to ANA [53], sugarcane and soybean crops were historically mostly rainfed. However, a higher water deficiency and expansion mostly to the Centre-West are leading to greater irrigation needs (currently 2 Mha, according to ANA, 37% in São Paulo state and 19% in the Centre-western state of Goiás) [11,54–57]. Indeed, ANA projects that between 2017 and 2030, irrigated agricultural area will increase from 6.95 Mha to 10.1 Mha [53].

Sugarcane is the third largest commodity in production value (Figure 1) and is a crucial food and energy crop for Brazil [58]. Sugar and ethanol production and bagasse-powered electricity plants reveal a strong water-energy-food interlinkage. Brazil is the world's second largest ethanol producer, with an output of over 26.5 trillion litres in 2017 [59]. In 2018, 29.74 billion litres of ethanol were consumed by Brazilian vehicles [60]. Over 80% of light vehicles sold have the *Flex Fuel* technology, whose motor is compatible with any gasoline and ethanol combination [61].

While ethanol is currently the most commonly used biofuel in Brazil, recent policies - especially Renovabio - aim to grow the share of biodiesel in the diesel mix. Legislation has increased the share of biodiesel from 2% in 2008 to 10% in 2019 [62]. Freight transportation predominantly in road vehicles makes diesel the most commonly used fuel in Brazil, accounting for 17% in 2018. Between 2017 and 2018, biodiesel consumption increased 26% from 3.31 million toe to 4.17 million toe [2] [63].

Regarding electricity, most generation in Brazil comes from hydropower (64.9% in 2019) [63], revealing a clear and traditionally recognized interlinkage between water and energy. Noticeably, hydroelectricity generation has played an important role in keeping the Brazilian electricity generation mix largely renewable. Maintaining a high share of renewables is necessary not only to meet Sustainable Development Goal (SDG) 7 on affordable and clean energy, but also SDG 13 (climate action) helping to ensure that the Brazilian economy develops sustainably [64].

[2] Tonnes of oil equivalent.

Hydropower generation, however, has seen its share of the Brazilian electricity generation mix lose ground from almost 85% in 2012 to 64.9% in 2019 [65,66]. Conventional thermal plants, on the other hand, are increasing their share and the national system's marginal operating cost [67]. Irreversible shifts in seasons [68], as well as concern about the environmental impacts, pose a challenge for hydropower expansion, and therefore the share of hydropower is expected to continue to fall. Recent projections for the electricity sector in Brazil have shown that by 2030 and continuing to 2050, hydropower installed capacity will have stagnated and therefore its share will have decreased or remain stagnant [69–73].

In Brazil, since the 1990s, the construction of new hydropower dams has been avoided due to the socio-environmental impacts, particularly the flooding of indigenous reserves and biodiversity loss. Since then, run-of-the-river projects have been prioritised, reducing the system's firm energy [69], but contributing to SDG7 [74–76].

This energy source is threatened by the 2013-15 drought and changes in the rainfall regime, highlighting vulnerabilities in water access and leading to increasing electricity prices [70,72,77,78]. The percentage of households using wood as a cooking fuel has risen from 16% in 2016 to 20% in 2019 due to this price increase [26], thus revealing an interlinkage between energy, water and land.

Wind energy is seen as one of the main alternatives to hydropower and experienced a ten-fold increase in the share of the electricity mix from 2012 to 2017. Wind now accounts for 8.25% of Brazil's total installed capacity, at 13.19 GW [79]. Since 2011, its installed capacity has increased over nine times, with more than US$28 billion invested in wind power projects between 2006 and 2016 [80]. According to the National Electric Energy Agency (ANEEL) [81], the potential for wind power generation in Brazil is 143 GW - 23 GW below the current total national power generation installed capacity, which was around 166 GW in August 2019 [79,81]. Almost half of this potential, 75 GW (around 144 TWh per year) lies in the North-East, the poorest region of Brazil. The region has historically suffered long annual droughts and wind power is currently seen as a means of development. Energy generation is an important pressure point in rural areas of Brazil, particularly in the Amazon region. Power transmission lines become scarcer towards the North region, and decentralised, systems dominate in this region (Figure 2). Brazil has nearly reached universal access to electricity, mainly through the *Light for All* programme [82] (Table 1). The remaining 213,000 households who do not have access to electricity are concentrated in the North and Northeast regions [26]. Most of the hydropower potential of Brazil remains in the Amazon region and will remain untapped under current environmental regulation [69,72,83–88]. As a result, several different decentralised energy sources, such as solar, wind and biomass, are being adopted and tested to provide energy access in the Amazon [78,89–94].

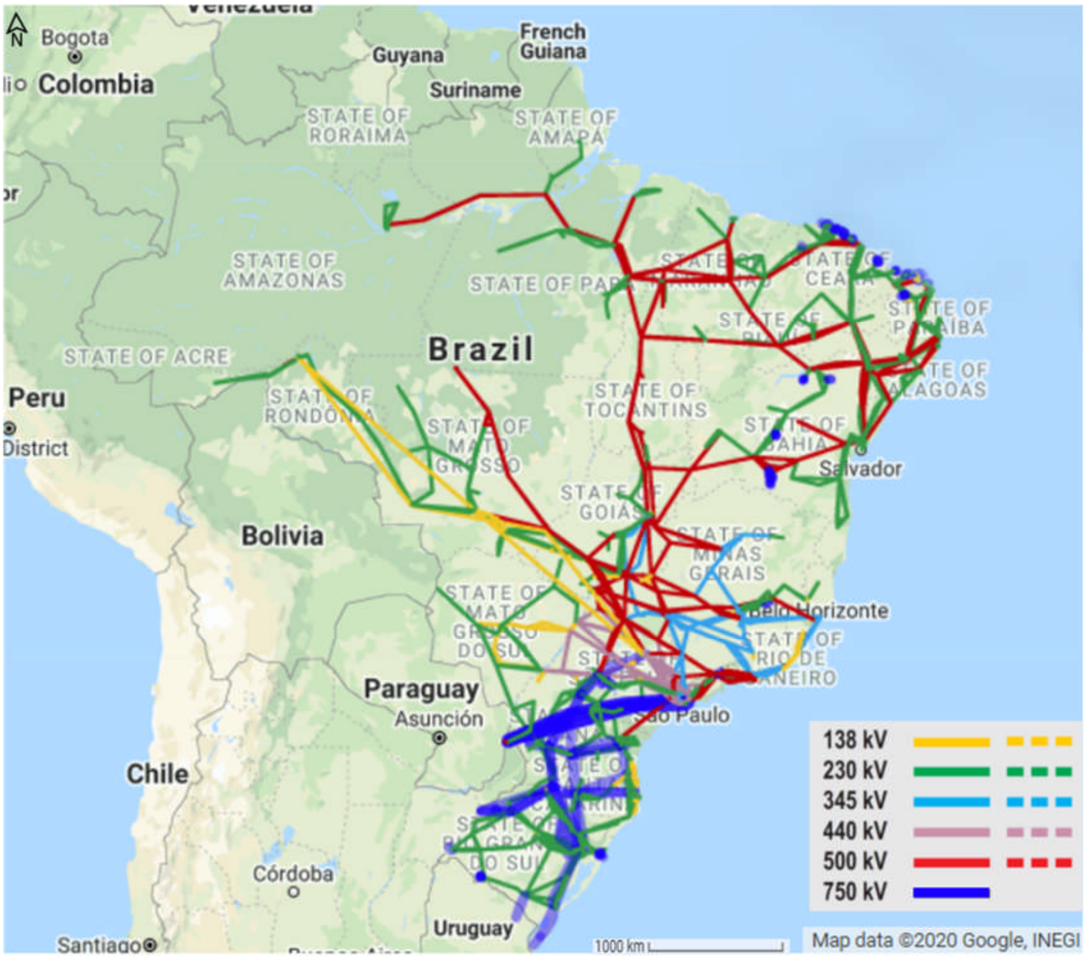

Figure 2. Existing and planned electricity transmission in Brazil, 2017

Source: Adapted from [95]

Waste management faces numerous challenges across Brazil, but most critically in rural areas. As of 2015, 77% of rural households rely on cesspits for sewage collection and 62% of solid waste is burnt or buried in properties [26] (Table 1). Waste energy practices are starting to gain ground with biogas technologies. Solid urban waste accounted for 95% of the 120 MW biogas electricity installed capacity, but agricultural waste is responsible for 29% of the amount of biogas produced in 2015, and 91% of the calculated potential for biogas in Brazil, both for thermal and electric energy [96,97].

In order to realise this potential, in 2017 the Brazilian government created a national biofuel policy called RenovaBio. It aims at increasing the share of bioenergy in the national energy mix by assessing and certifying the environmental performance of first and second generation ethanol, biodiesel, biojet fuel and biogas [97,98]. Studies performing future projections for the Brazilian energy mix generally consider biogas a relevant alternative, but results do not show it as gaining scale in the short term [69,70,99].

3. Review methodology and interlinkage classification

3.1 Definition of Resource Use and Management Practices

The concept of resource use and management practices utilised refers to technological and organizational options adopted by rural Brazilian populations and service providers of water, food, energy and to provide a destination for waste. Thus, it refers to practices regarding clean water provision for households, agricultural water uses, water treatment, energy generation technologies, agriculture and livestock activities and techniques that produce food goods for the population, solid waste and effluents disposal, sewage collection and treatment. Therefore, the concept of practices used here refers to upstream to downstream resource management practices.

Krueger et. al [20] and the European Commission [21] define natural resource management as a means of coping with resource scarcity and ensuring their sustainability across time. This includes managing the extraction of scarce resources and avoiding environmental pollution.

The International Resource Panel [5] points out that resource efficiency is vital for a transition to sustainable practices, and should be obtained by a smart integration of public and private governance.

Water, energy and food, for example, are resources that provide fundamental services for livelihoods [22]. Rural areas of developing countries are particularly important in providing access to these basic resources and services. Agroecosystems degradation deprives populations of key resources, especially affecting those communities that rely heavily on agriculture and livestock [23].

We therefore analyse how communities in Brazil obtain access to water, energy, food and waste management provision systems, as well as current and emerging techniques to ensure their sustainability in the longer run. Traditional practices can involve more than one resource, such as hydropower involving water and energy [24,25], or irrigation involving water and food. However, findings show that most emerging techniques which are more focused on long-term sustainability of resources and increased population access, tend to optimize resource use and therefore explore synergies between two or more resources. For this reason, we analyse the aforementioned interlinkages between resources and how each practice impacts them.

3.2 Review methodology and publication distribution

We searched the 'Scopus' and 'Web of Science' databases for the keywords "*water*", "*waste*", "*food*", or "*energy*", combining each of them with the keywords "*practices*" "*rural*" and "*Brazil*". The operator "AND" was used to combine the latter three keywords. We searched peer-reviewed journal articles, academic dissertations, and grey literature reports from the federal and state governments, published from 2000 to 2020, in the English and Portuguese languages. Searches resulted in the assessment of 630 documents' titles and abstracts to create the final selection, excluding those which did not match the criteria.

Articles were selected for review based on the following inclusion criteria: (i) they were case studies describing resource use and management practices utilized in Brazil; (ii) they described specific use and management practices for one or more of the resources analysed; (iii) they focused specifically on rural areas; (iv) emerging techniques analysed are currently used in Brazil even if at small-scale, meaning studies reviewed were not assessments of hypothetical potentials and/or future projections. From 630 documents identified, 142 met the inclusion criteria and were reviewed for this research. In addition, national data sources as the National Household Sample Survey (PNAD) [26] and the National Energy Balance [27] were reviewed , since they list practices. Figure 3 below shows the schematic flow of the systematic review method adopted.

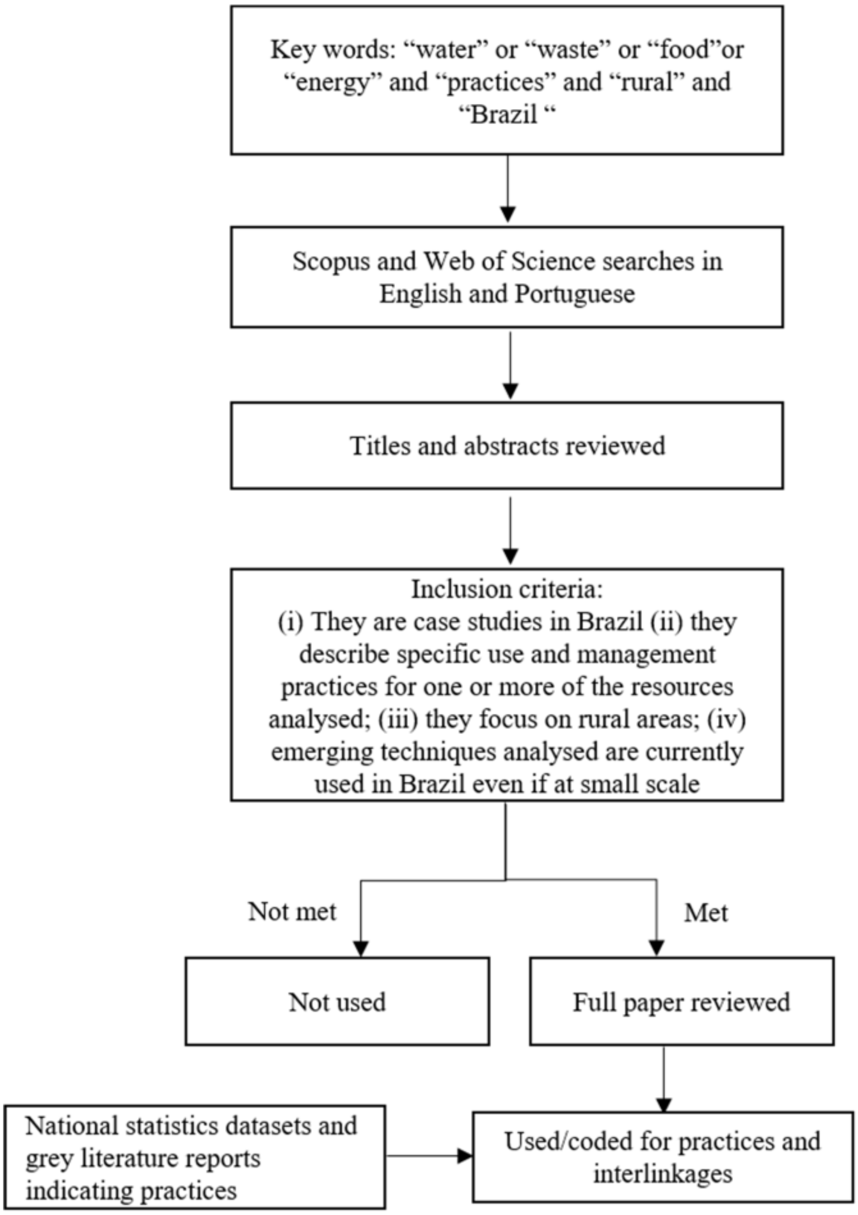

Figure 3. Systematic review method flowchart

For consistency, studies which did not meet all the inclusion criteria were omitted. For example, some studies were focused on urban areas, while others did not describe resource use and management practices.

For instance, studies relating to food that assessed calorific intakes of households without specifying how the food was obtained. Other examples include studies which analyse water quality at a specific water body, but do not describe water uses affecting these conditions.

Papers were first grouped by resource keywords: papers identified under “water”, “waste”, “energy” and “food” keyword searches formed four groups, one for each resource.

The distribution of the 142 papers into resource groups is shown in Figure 4. Noticeably, papers found under “energy” and “food” considerably outnumber those found under keywords “water” and particularly “waste”.

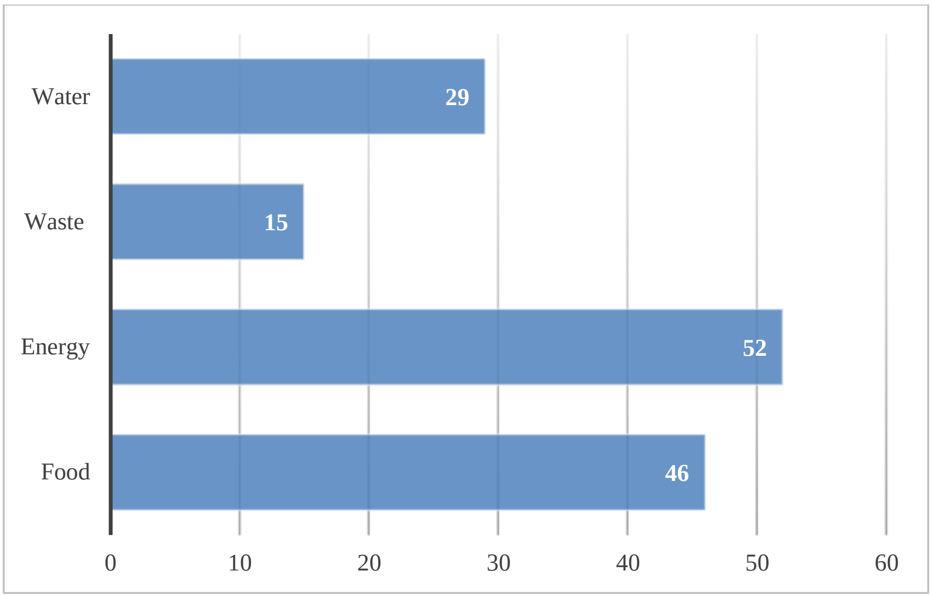

Figure 4. Number of papers per main resource analysed

We observed an overall concentration of publications from authors based in the state of São Paulo (Figure 5). This was expected since most of the international publications from Brazilian authors come from universities in São Paulo – 42% of all 53.3 thousand publications with at least one author based in Brazil in 2016 had authors in the state of São Paulo [28]. We noticed a particular concentration of analysis focusing on water resources in the State of São Paulo starting in 2013, with 6 to 7 papers published per year from 2016, following the major water crisis the state is experiencing. Energy research was also concentrated in São Paulo. It is the largest energy consuming state in the country, representing 28% of Brazil's total energy consumed in 2017 [29], and has seen the water crisis hinder its hydroelectricity generation.

The Amazon region represents another cluster of energy research (7), mostly due to energy access issues and decentralised systems. The renewable energy generation potential of semiarid states such as Minas Gerais and the North-East, mean these states are also a focus of energy research. Research focused on food production is distributed throughout the country, but there is a focus on rural and North-Eastern states, where famine has historically been a concern.

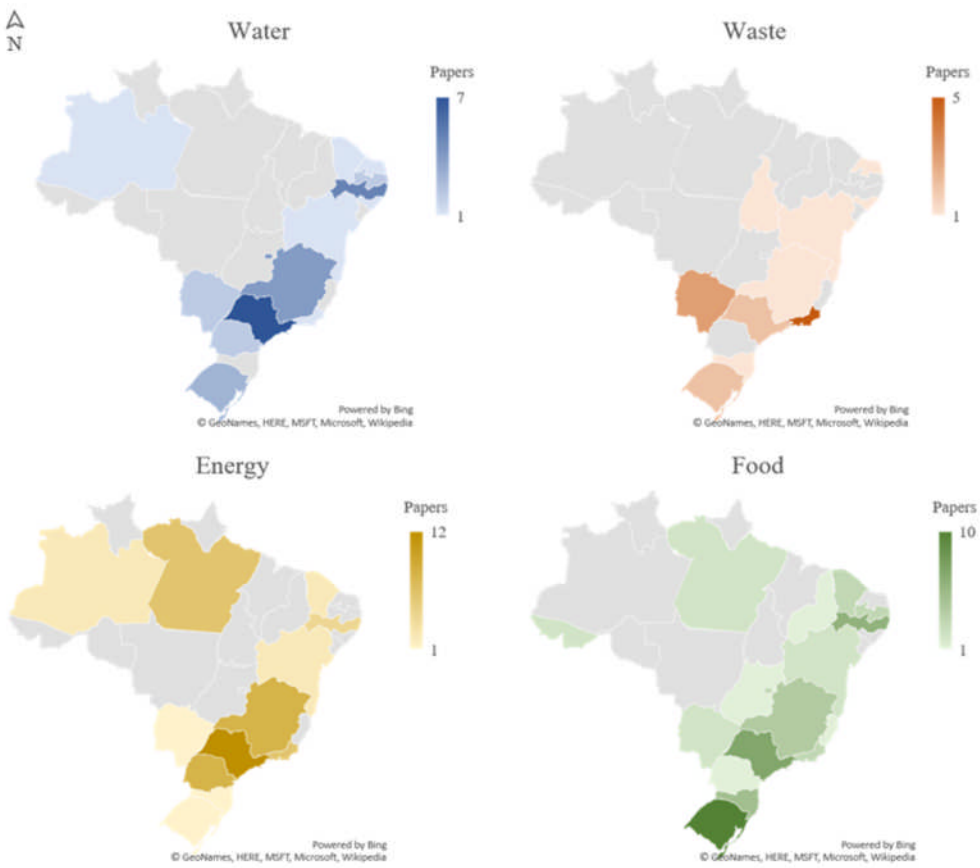

Figure 5. Geographical distribution of paper authors per main resource analysed

This research reviewed papers published between 2000-2020. A strong temporal concentration from 2010 is noted though, as 89% of the papers reviewed were published from this year onwards. Publications focused on water also increased from 2014 onwards, following the major drought experienced since 2014 which has caused impacts on agriculture, electricity generation and household water provision.

The greatest number of papers is focused on energy generation (n=50). Similarly, “energy” is the most frequent term found in the names of journals where papers were published (n=31). Papers focused on water, waste and food rarely featured in journals relating to the specific resource, but rather in broader, interdisciplinary fields such as environment, policy and sustainability**.**

3.3 *Finding interlinkages*

All papers reviewed were coded according to the main resource analysed and the interlinkage to identify resource use/management practices and the interlinkages they describe. The process was conducted as follows: (i) group papers according to practice described; (ii) identify how many resources the described practices involve; (iii) analyse how each of the resources is impacted; (iv) select critical interlinkages according to their incidence in the literature, number of resources impacted, and scale of use in the national context. Quantitative indicators were used to determine the criticality of resource interlinkages. Critical interlinkages are synergies and trade-offs which pose fundamental challenges and opportunities in resource provision for Brazil's population. In order to find interlinkages, the nexus matrix (Figure 6), inspired by Biggs et.al [2] was used as a starting point.

	Water	**Waste**	**Energy**	**Food**
Water	Water provision			
Waste	Sewage and effluents	All waste management		
Energy	Water use for energy generation, hydropower and energy crop irrigation	Waste energy generation (biodigesters), waste-water treatment	Energy generation and provision	
Food	Irrigation, deforestation, soil management, fishery, livestock consumption	Manure, vinasse fertilising	Bioenergy crops trade-off with food crops, energy consumption for food provision	Food production practices

Figure 6. Expected resource interlinkages matrix

Resource use, management practices and the bilateral interlinkages described in the matrix were used as assumptions for assessing the actual practices found in the review. In other words, the matrix shows an overall view of practices involving each pair of the analysed resources that were expected to be found in the literature.

A limitation of the systematic review method developed here is the exclusion of non-indexed papers published in Brazil. While these may represent a relevant share of Brazilian publications, papers which do not appear in Scopus or Web of Science were not included. Further, the analysis performed here is static and focusses solely on the current status and trends in the existing literature on resource use and management in Brazil.

4. Results – mapped single resource-focused practices and their embedded interlinkages

The review found 135 different management and use practices for water, waste, energy and food throughout Brazil. Practices were divided into eight groups according to the main use of each resource, as shown on Table 2. As shown in Figure 4, while energy has the largest number of papers (50), it has the fewest number of practices (30) (Table 2), showing a concentration of papers describing the same practices. On the other hand, waste, whilst having the smallest number of papers (14), showed a large number of practices (33). Water also has a larger number of practices identified (34) than papers focused on this resource (26), meaning on average more than one practice was described per paper. Papers focused on food production and provision were more balanced, with 46 papers describing 38 practices.

Table 2. Types and number of practices per resource

Resource	Type	No. of practices
Water	*Agricultural water use*	21
	Household water use	8
	Water treatment	5
Waste	*Solid waste disposal*	9
	Effluents/sewage	15
	Agricultural waste disposal	9
Energy	*Electricity*	21
	Thermal energy	9
Food/land		38
Total		135

The most frequently described practices in the literature are family-based agriculture for food (40), solar and biomass-fired power plants for energy (22), cistern – rainwater harvesting for water (13) and manure biodigester for waste (10). Figure 7 shows the full list of practices found in the literature and the number of papers that described each practice.

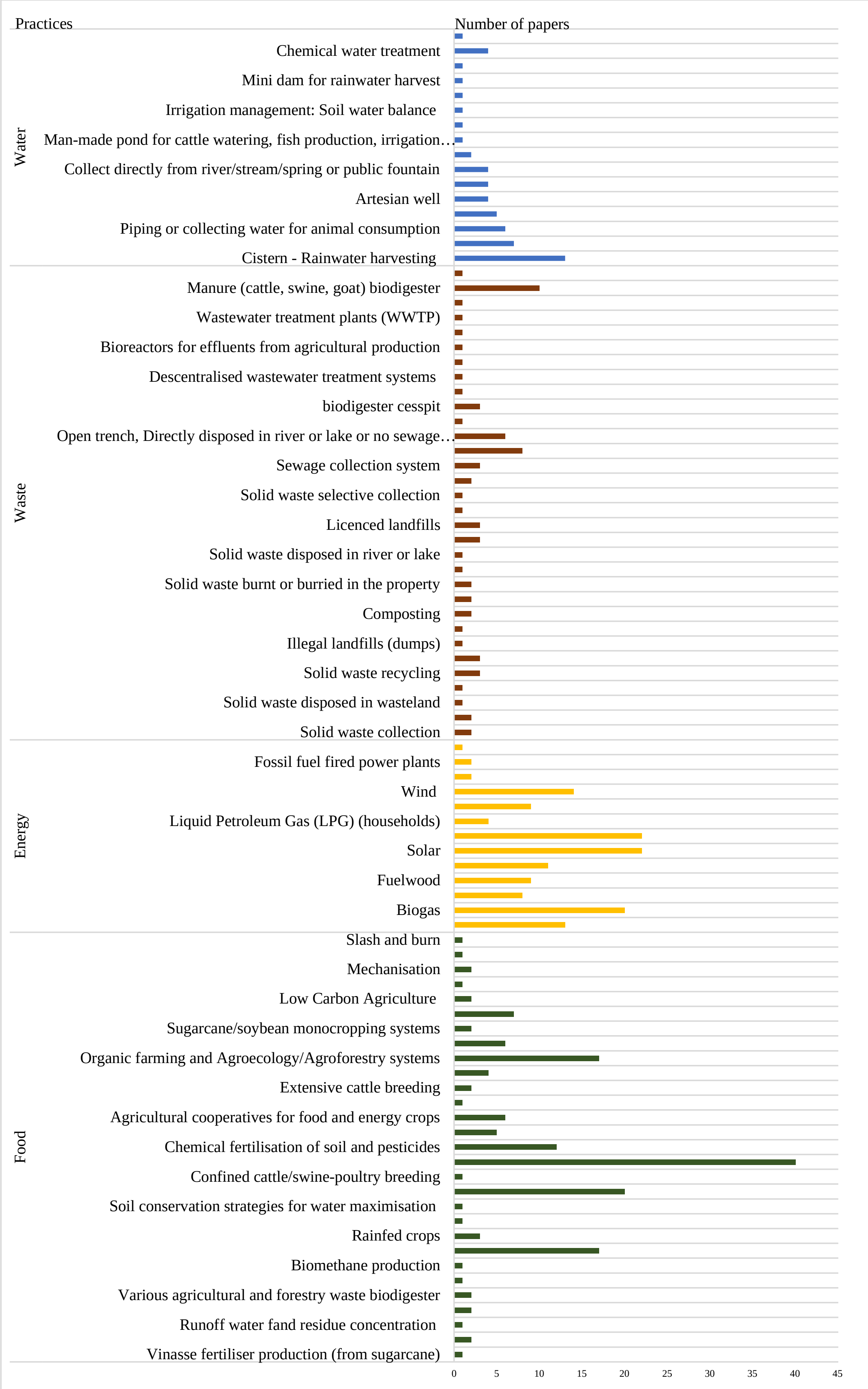

Figure 7. Number of papers by practice identified per main resource analysed

Figure 7 shows that cisterns have become a particularly relevant practice for water use in rural Brazil. This relates mostly to a government program called “A Million Cisterns” (*Um Milhão de Cisternas*, in Portuguese). Created in 2003, the program aimed to provide water access to rural populations in the Northeast Semiarid region [100,101]. The next most common water practices described by the literature are agricultural uses of water, namely: draining local river basins for irrigation (7) and water collection for animal consumption (6). This was expected, since according to ANA [51], 52% of total water withdrawal in Brazil is directed to irrigation and 8% to animal use.

The concentration of waste-focused papers in manure biogas reflect the potential of Brazilian agriculture to generate this source of thermal energy and electricity. Although current manure biodigesting is still quite low (1.6 million m^3/day), the Brazilian Biogas Association (ABiogas) estimates that 91% of the 78 million m^3/day of Brazil’s biomethane could be derived from agricultural waste [97,102]. The following most frequent practices found in the literature regarding waste management refer to the mostly utilised and less adequate sewage practices: cesspits (8), open trench or directly disposing into water bodies (3).

Biomass and solar were also commonly referred to in the literature. While biomass-fired thermal plants are, at present, an important renewable technology for Brazil’s electricity mix, solar power is highly cited by the literature due to its very large potential, rather than current use. Biomass already accounts for 9.2% of Brazil’s electricity installed capacity, most of which is sugarcane bagasse at 46% of total power sector fuel consumption [27]. At a current installed capacity of 2.1 GW, solar power accounts for merely 1.27% of Brazil’s total. However, it is rising steeply, and between 2017 and 2018 solar power supply increased by 316% [79]. In general, bioenergy is well represented in the literature: both fuelwood and biodiesel were described by nine papers each. Wind energy, the main trend in terms of renewable alternative, was also highly analysed with 14 papers focusing on this source. Hydropower, as would be expected since it is the main electricity source, is analysed by 13 papers. As discussed, family-based agriculture is responsible for the majority of food produced in Brazil, and this is reflected in the literature.

4.1 Interlinkages

From the 135 practices found in the 142 papers reviewed (Table 2), 48 papers (35%) focused on two or more of the four resources analysed. Among the interlinkages, 41 practices focus on food, 35 on water, 25 on waste and 13 on energy. Practices were therefore categorised for the resource interlinkage they comprise, namely: “Water, energy, food and waste”; “Water, energy and food”; “Waste, energy and food”; “Water, energy and waste”; “Waste, water and food”; “Waste and Water”; “Waste and energy”; “Water and food”; “Water and energy”; “Waste and food”; “Energy and Food”. The numbers of papers referring to each of the interlinkages are represented in Figure 8.

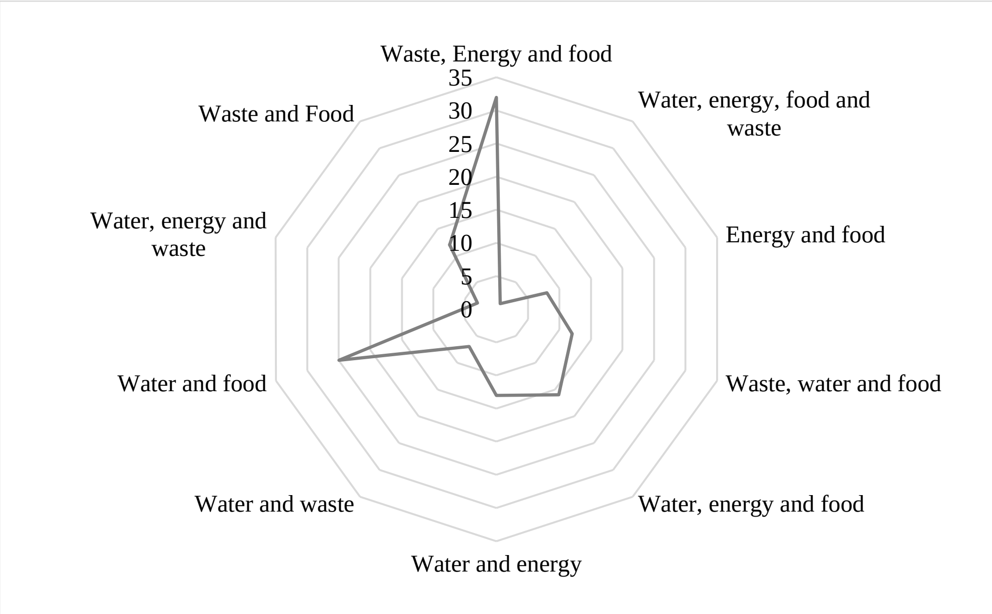

Figure 8. Number of papers referring to each resource interlinkage

Waste, energy, and food is the most common interlinkage (31). Papers in this category analysed waste bioenergy generation, specifically thermal electricity generation fired by sugarcane bagasse, electricity cogeneration in sugarcane processing plants, forest-waste biomass thermal power generation, biogas generation technologies, manure and crop waste biodigesting, and the simple waste burning technique. This focus on biogas generation from agricultural waste reinforces that, although biogas is yet to reach scale in Brazil, researchers seem to expect it to become an important renewable alternative.

The second most frequent interlinkage found in the literature is “water and food” (29 papers), also showing that irrigation is crucial to understand critical resource interlinkages in Brazil. This is because all 16 practices with this interlinkage relate to agricultural uses of water. Small-scale family agriculture practices that encompass synergies in resource access are particularly relevant given the importance of family agriculture in food production in Brazil. 22 papers investigated practices identified as conducted by family farmers or developed by the Brazilian Agricultural Research Corporation (EMBRAPA) to be family-farming friendly. Among them are simplified irrigation techniques such as bubbler irrigation, superficial irrigation with furrows and plastic canvas by the bed of horticulture, which save irrigation water and thus are especially useful in the Northeast Semiarid [103].

“Water, energy and food” follows with 16 papers. These resources are involved in practices regarding irrigated energy crops, namely irrigated sugarcane and soybean crops. They also include one of the main practices which leads to indirect changes in water provision: deforestation for pastureland expansion, which degrades soil and harms the quality of nearby river basins [104], as well as affecting rainfall regimes. Rainfall regime changes directly affect hydropower dam levels and therefore electricity provision.

“Water and energy” come next in terms of the number of papers (13), all of which refer to hydropower. “Waste and food” follows with 12 papers. “Waste and food” are linked in practices related to soil preparation (biofertilizer and manure), landfills and decentralised wastewater treatment using food waste.

“Waste, water and food” are interlinked in eight practices described in nine papers. Six of them relate to effluent treatment for uses as irrigation and soil preparation. Emerging low-carbon agricultural practices also interlink these resources, as crop-livestock-forest integration, degraded pastureland recovery and animal-waste treatment.

Energy and food are interlinked by three practices regarding biodiesel and fuelwood plantations and are described by eight papers. “Water and waste” interlink in sewage disposal practices: rudimentary and septic cesspits, widely used in Brazil as previously mentioned, sewage direct disposal in water bodies with or without treatment and simplified water treatment techniques using recycled materials as PET bottles. Water, energy and waste are discussed in one practice, biodigester cesspits, which is a biogas technology that is described by three papers.

The four resources, “water, waste, energy, and food”, are linked by only one practice, which is examined in one paper: second-generation ethanol - an energy source obtained from food goods, involving cellulose from agricultural waste and irrigation water [105]. However, it is important to note that second-generation ethanol is not yet produced at a commercial scale in Brazil.

Under “waste and energy” biodigester cesspit manure is mentioned, while other agricultural waste biodigesters fall under “waste, energy and food”. These technologies enable small-scale family farming to produce biogas on their properties [106–110]. An advantage of these technologies is that they can be integrated with other resource-optimising family farming practices; for example, in 2002, EMBRAPA created an integrated system for food production called the “EMBRAPA Small System”, a technological alternative for small rural communities suffering from water scarcity [103]. This system has been most widely adopted in the Brazilian Semiarid region and integrates aquaculture, poultry and other small animal husbandry, small horticulture, hydroponic farming and biogas production. This system is currently used in seven Semiarid states: Maranhão, Piauí, Ceará, Pernambuco, Bahia, Minas Gerais and Tocantins [103]. Another practice targeted at small rural communities is simplified water treatment techniques using recycled materials such as PET bottles and PVC tubes. These are also relevant in areas where access to clean water is critical, mostly the Semiarid region.

The final category was “energy and food”. Small-scale firewood production providing for energy needs is a widely used practice in rural Brazil. Wood is currently used as a cooking fuel for 20%, or 14 million, Brazilian households [26]. As mentioned, since 2016, increased electricity prices have led three million households to revert to cooking with fuelwood [26]. It is therefore a critical interlinkage between energy and food, especially as fuelwood competes with food production in small farms. Linkages between energy and food also occur in smallholder agricultural cooperatives between food, biodiesel and ethanol production in mini distilleries [111–114]. However, as such cooperatives are not common in Brazil, this example does not have the same importance as fuelwood.

Table 3 lists practices grouped in interlinkages and the sources which describe them.

Table 2. Practices per resource interlinkage

Resource	Practice	Sources
Water, energy, food and waste	Second generation ethanol (cellulosic, from bagasse)	[95]
Water, energy and waste	Biodigester cesspit	[93,105,106]
Waste, water and food	Pesticide container collection and triple washing of glass and steel containers	[107]
	Vinasse fertiliser production (from sugarcane)	[108]
	Runoff water from grain production and residue concentration from confined animal breeding (swine, poultry and dairy)	[109]
	Chemical fertiliser and pesticide disposal in streams	[110,111]
	Treated sewage subsurface drip irrigation	[112,113]
	Vinasse fertigation	[108,109,112]
	Confined cattle/swine-poultry breeding	[109]
	Direct planting - no ploughing/tilling (beans and grains)	[93,114–116]

	Low Carbon Agriculture (Integrating crop-livestock-forest: recovering degraded pasturelands, treating animal waste)	[117,118]
Waste, Energy and food	Sugar cane bagasse-fired thermal plants - centralised and decentralised/cogeneration plants in sugar cane mills and other agricultural residues (babassu nuts)	[44,49,62,71,119–123]
	Wood biomass fired thermal plants (forest waste) - centralised and decentralised	[44,62,70,71,73,119,124–128]
	Biogas/photovoltaic hybrid power system decentralised - NE Semiarid	[129]
	Manure Biogas	[23,44,93,96–99,129–133]
	Crop/forest waste biogas	[97,119,128]
	Burnt agricultural waste	[44]
Water, energy and food	Irrigated sugar cane and soybean crops for energy purposes	[24,49,93,104,108,112,134,135]
	First generation Ethanol	[20,24,49,95,136–138]
	Deforestation for new pasture and croplands	[34,93,110,117,118,139]
Water and energy	Hydropower (large, with reservoirs, and small)	[44,51,62,71,73,120,125,127,140–143]
Water and food	Draining local river basins for irrigation (dripping and aspersion)	[50,51,93,135,144–146]

	Piping or collecting directly from streams and wells for animal consumption	[93,108,141,145,147]
	Man-made pond for cattle watering, fish production, irrigation and erosion protection.	[93]
	Water reuse in dairy cattle farming	[93]
	Irrigation management through soil water balance (irrigation sensor, critical soil humidity control)	[93]
	Underground dam	[93]
	Mini dam for rainwater harvest	[93]
	Family farming friendly irrigation practices: Bubbler irrigation, superficial irrigation with furrows, plastic canvas by the bed.	[93]
	Freshwater irrigated food crops	[50,93,122,141,144,145]
	Integrated fish, poultry and other small animals, small horticulture, hydroponic farming (*Sisteminha EMBRAPA*)	[93]
	Soil ploughing/tilling (beans and grains)	[114–116,148]
	Minimum tillage	[114–116]
	Organic farming and Agroecology	[118,148–155]

	Slash and burn	[93]
	Simplified systems for treatment of water with low-cost technology to meet the immediate demand of rural communities, such as the simplified diffusion chlorinator (plastic vessel - PVC tube or PET bottle).	[156]
Water and waste	Septic cesspit	[58,157–159]
	Rudimentary cesspit	[58,157–159]
	Directly disposed in river or lake	[58,109]
	Sewage treatment before disposal in river or lake	[109]
	Licenced landfill	[160]
Waste and Food	Manured soil/biofertilisers	[23,97,98,109,110,130,149,151,161]
	Direct planting - no ploughing (beans and grains: soybeans, corn, wheat)	[109]
	Decentralised wastewater treatment systems	[162]
	Biodiesel/Palm oil biomass mixed with diesel in generators	[74,142]
Energy and food	Agricultural cooperatives for food and biodiesel plant, ethanol or charcoal production	[101–104,163]
	Small scale firewood production for energy need (Eucalyptus)	[164]

5. Discussion - Critical interlinkages and trends identified

Drawing on the assessment of interlinkages between resource use and management practices discussed in Section 4, we identified critical interlinkages, which we argue should be prioritised in in future research.

Critical interlinkages have been identified through the analysis of how representative a practice is in the country as a whole, and if the relevance of the synergy or trade-off embedded in the resource interlinkage. Thus, widely used practices which involve scarce resources, such as water during drought periods or in the Semiarid region, or resources whose protection is a challenge, for example deforested land, are considered critical. Table 4 systematises quantitative indicators obtained from the literature and official statistics which were used to establish levels of criticality.

Figure 9 shows how water, waste, energy and food interlinkages translate into the practices found through the systematic review. Broader groups of practices are shown for practices including only one resource and they narrow down into more specific groups of practices as they interlink two to four resources. For example, there are many water provision practices , but when it comes to those that involve both water *and* food there are just two clusters: crop irrigation and water for livestock; and water and energy.

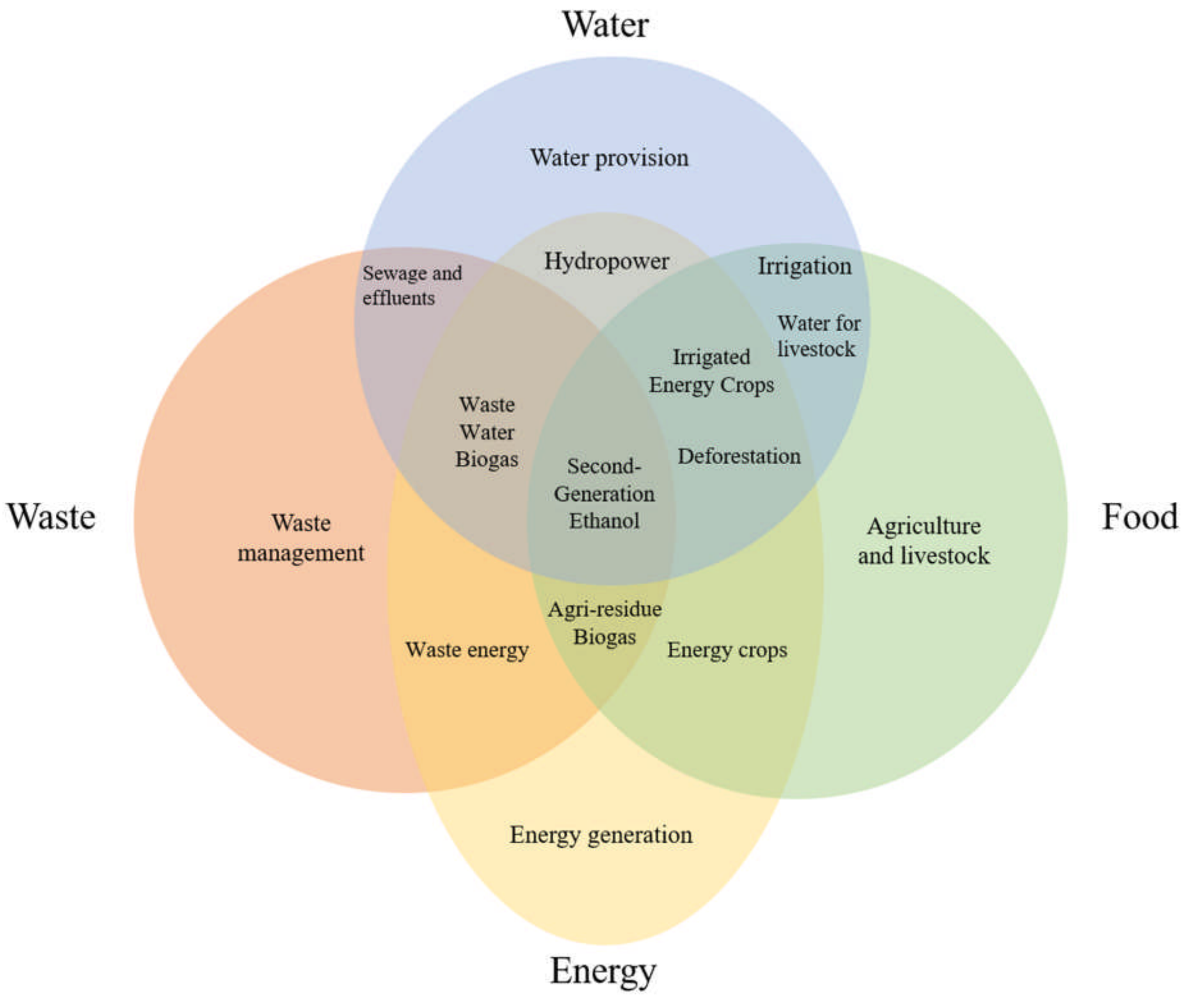

Figure 9. Practices and the Resource Nexus in Brazil

Table 4 below shows shows how representative in terms of national scale each practice is in relation to each resource cluster shown in the representativeness of each practice indicated in Figure 9 to each of the resources involved through selected quantitative indicators.

Table 3. Interlinkages relevance indicators

	Water		Energy			Food		Waste	General relevance indicators
			Ethanol 1G[3]	**Bagasse Electricity**	**Ethanol 2G**[4]				
Sugarcane ethanol and bagasse-fueled electricity	29% of total irrigated agricultural area in 2017 [53]	Water footprint of dripping irrigation to produce ethanol: 1.410,07 L_w/L_e [115];Water footprint of sugarcane 114–190m^3/t [11]	6.4% of total energy consumption, 19% of transport energy consumption, 15.73 Mtoe in 2018 [63]	11% final energy consumption, 30% of thermal power 2018, 40GWh [63]	10 ML produced in 2019, 0% of total energy consumption [63]	Sugarcane represents 12% of total agriculture and livestock commodity 2010-2018 [52]	9 Mha of sugarcane plantions in 2018 [103]	Total bagasse produced: 157.764 tonnes in 2018 [63]	Over 80% of light vehicles sold from 2010 to 2017 are FlexFuel technology [61]
Hydropower	Dam water evaporation: second largest water consumption in 2017: 669 m^3/s [53]		407 GWh – 64.9% of total electricity generated in 2019 [65]						Share in the electricity mix has fallen from 82% in 2011 to 64.9% in 2019 mostly due to changing rainfall regimes [65,116]
Irrigated agriculture	792 m^3/s in 2017, 68.4% of total water consumption in 2017 [53]					6.95 Mha irrigated agriculture in 2017 [51]			
Soybean biodiesel	900–2600m^3/t [11]		3.13 Mtoe consumption in 2018, 1.2% of total energy consumption, 3.3% of transport sector energy consumption [63]			Soybeans 21% of total agricultural and livestock commodity GPV[5] [52]	35.3 Mha of Soybean plantation in 2018 [103]		3% of total soybean yield used for biodisel production. Soybean biodiesel is 75% of total biodiesel [117]

[3] First Generation Ethanol
[4] Second Generation Ethanol
[5] Gross Production Value

Water for livestock	1,935-9,673 L/kg of beef-semiconfined cattle [118]	125 m^3/s - 10.8% of total water consumption in 2017 [51]			Beef, pork and poultry account for 26% of total agricultural and livestock commodity GPV [52]		
Deforestation	Rainy season delay of 0.12–0.17 days per percent due to increase in Amazon deforestation [119]		Up to 29% negative impact on hydropower generation in the Amazon Basin [119]		Rainfall regime changes caused by deforestation could decrease soybean production up to 10% [119]		9,762 km2 of the legal Amazon[6] was deforested in 2019; 160,335 km2 cumulative since 2004, 70,000 km2 or 17% of total area deforested [120]
Biogas			2.37 GWh generated in 2018, <1% of total electricity generation [63]	Installed capacity 140 MW [63]; potential 4.3 GW [121]		95% of current installed capacity is urban solid residues, but this is only 7% of total potential. 48% of total potential sugarcane vignasse and 45% other agroindustrial residues [121]	

[6] Legal Amazon (Amazônia Legal, in Portuguese) is an area of over 6 million km2, 60% of Brazil's total area, established in 1953 for the economic development planning and deforestation control of the Amazon [239].

Hydropower is clearly critical for Brazil, with most electricity generation based on this source (66% in 2018, Table 4). Recent droughts have revealed a major vulnerability (decrease from 82% in 2011 to 66% in 2018 [122,123]) and a trade-off between water and energy . It is therefore necessary for Brazil to find alternatives to maintain the renewable profile of its electricity generation mix and meet SDG7.

This trade-off is widely acknowledged and the literature reviewed here contains numerous analyses of non-hydro renewable electricity sources, such as wind and solar power, bioenergy and biogas.

However, this analysis has highlighted some of the potential trade-offs. For example, Renovabio may lead to an increase in water use due to the expansion of sugarcane plantations.

Power capacity expansion policy should also overcome the energy-water trade-off in hydropower with such sources to promote social and economic development, access to clean energy, and energy security simultaneously, while also giving enough emphasis to water scarcity. The Northeast region has also been the most affected by increased electricity prices since the drought started in 2014, as evidenced by the increase in fuelwood demand. The most relevant synergy to be explored in this sense is increasing wind and solar energy generation in the Northeast to attain energy security and access while releasing the pressure on water resources.

Bioenergy also plays a major role regarding transport fuel, mostly through ethanol but increasingly through biodiesel. Ethanol accounted for 18.8% of total transport fuel consumed in 2018 in Brazil (Figure 4), while gasoline and diesel accounted respectively for 25.8% and 43.6%) [63]. Biodiesel is still incipient (3.3% of transport energy consumption, Table 4). However, its demand is expected to increase, as from September 2019 the biodiesel mandate in the diesel mix will be raised once more, from 10% to 11%. The National Council for Energy Policy (CNPE) has even approved to expand this share to 15% in 2023 [125].

Noticeably, bioenergy sources are interlinked between themselves, revealing trade-offs and synergies from their production and consumption. In addition to concerns about food versus fuel, competition for irrigation water among energy crops may become an increasingly important consideration. Providing an example of a synergy is that the increase in ethanol production has corresponded to an increase in sugarcane bagasse fired electricity generation [63]. This underlines the scale dimension of the nexus and the necessity to look at entire systems of provision in contrast to just a primary-resource specific approach.

The number of resources involved and papers found on the practice may be significant and indicate critical interlinkages, but the relevance of a practice to the country ultimately depends on the scale to which it is used.

Second generation ethanol, for instance, is the only practice which was found to involve all four resources analysed, with a synergy between energy and water, and within energy itself, as its main input is sugarcane waste. However, this technology is not yet commercially available. Thus, although second generation ethanol does not characterise a critical interlinkage, it is a rather important gap for future research, with merely one paper found analysing it. First generation ethanol, on the other hand, which involves water, energy and food, is clearly a critical interlinkage for the country, calling attention for the coordination of energy, land and water. Current governance structures do not integrate water governance mainly because sugarcane has traditionally been rainfed. However, a critical water governance trade-off emerges as rainfall regimes change and sugarcane plantations expand to the Centre-West, North and Northeast region.

Deforestation raises another critical interlinkage in Brazil between food, water and energy. Although this deforestation is not always accounted for within the resource nexus, its impacts on water provision are widely recognised by the literature on deforestation and climate change, and should be considered for water governance as well. Deforestation affects hydropower generation through changes in rainfall regimes, indicating an interlinkage between food, water and energy (Table 4). Hence a clear need emerges for coordination between regulatory bodies that govern land use, water and energy to tackle such trade-offs.

Deforestation is also linked with the increase in fuelwood consumption, adding energy access to the challenge. As shown, Brazil has attained access to electricity for over 99% of households but the increase in fuelwood consumption reveals that access may not mean purely a connection to the grid, but also the affordability of clean cooking fuels and technologies – mainly electricity. It thus raises the need for forest management policies considering multiple goals: pasturelands, biodiversity conservation, wood production, community livelihoods, water management and energy supply [4]. Furthermore, energy access policies should consider the importance of both grid connections and the affordability of electricity, which together can ease impacts over forests and consequently water resources. This is a major synergy and research gap to be explored by future studies. Figure 10 exhibits the relationships between hydropower, irrigated energy crops and deforestation with their effects on food, water and energy availability.

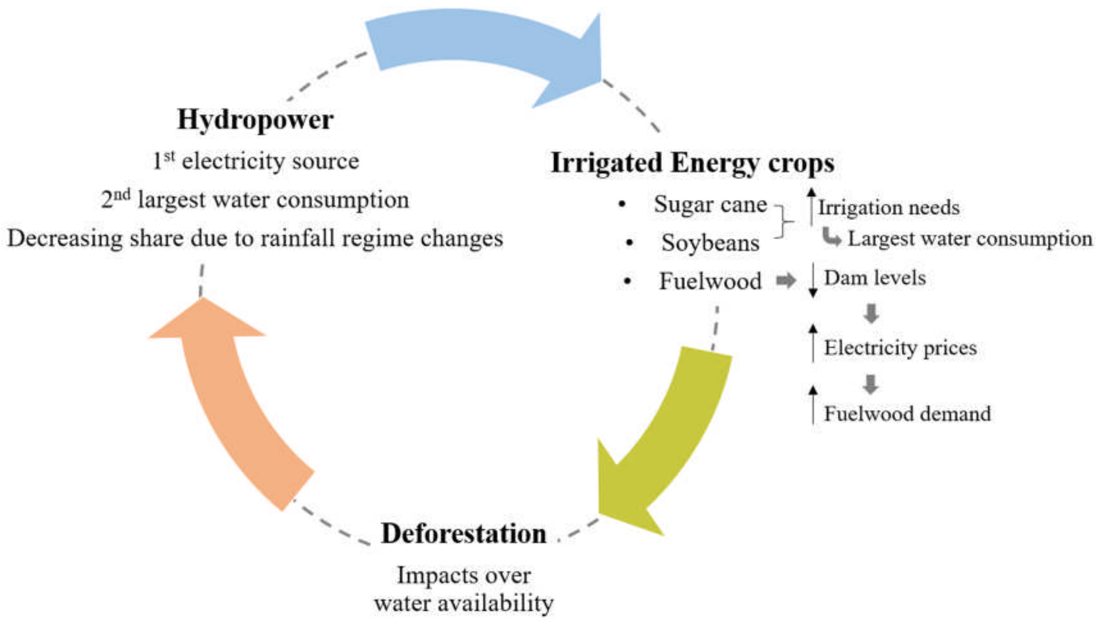

Figure 10. Circularity of synergies and trade-off between critical interlinkages in Brazil

Some of the new agricultural practices reviewed here are expected to create synergies between water and food, with some additional synergies with waste. For example, no-till methods which integrate agricultural waste can improve soil conditions and water quality.

Lastly, the production of biogas provided a critical link between waste, energy and food. Its prevalence in the literature reviewed illustrates that, while biogas is not currently widespread, researchers anticipate its increased use in Brazil. This is related to the potential of agricultural waste, which highlights the medium-term potential of biogas technologies. . Biogas also reveals potential synergies with the wider energy system; if biogas can scale, it may be used as a back-up for intermittent renewable sources such as wind and solar power. Further research should focus on the synergies between food production, waste management and energy generation that biogas opportunities may bring.

6. Conclusions and future perspectives

This paper aimed to provide an overview of research on the resource nexus research in Brazil and to propose a research agenda to explore the most relevant trade-offs and synergies embedded in interlinkages between resources. We systematically reviewed the resource management literature, raising the need for a stronger focus on the interlinkages rather than the single-resource approach adopted so far. We screened and reviewed 142 papers which analyse an exhaustive range of 135 upstream to downstream resource management practices. We then identified the interlinkages between two or more resources and which critical nodes should be investigated further.

This method is novel given the clear unaddressed need for resource nexus research to be geographically context-specific and focused on the most relevant, critical interlinkages for the region in question. Hence, the method presented here consists of a strategic step to set research priorities for the resource nexus in a country, in this instance Brazil. The vast majority of resource management literature for Brazil still treats each practice as relevant only to the main resource involved. This paper provides a perspective of all resource use and management practices for water, waste, energy and food, identifying the resource interlinkages embedded in the identified practices. Using quantitative indicators, it points out the critical interlinkages for further research to explore and centre the efforts to integrate resource governance.

Through this systematic review , it was possible to identify that, despite the single-resource focus of most analyses, 48 practices (36%) affect two or more resources. The critical interlinkages found that are yet to be explored by literature include: water-energy in hydropower, with synergies in wind and solar in the Northeast and sugarcane bagasse across Brazil, as means to meet the increasing demand for electricity while releasing pressure on water resource; energy-water-food in irrigated energy crops; ethanol, biodiesel, which are responsible for the rapid increase in irrigation areas, and fuelwood; and water-food-energy in deforestation, which builds pressure over nearby water bodies as well as rainfall regimes, with consequences over hydropower generation, thus closing the circle.

Our first policy recommendation suggests reducing hydropower pressure on water bodies through exploring alternative electricity sources, particularly wind and solar in the Northeast region of Brazil. An important synergy lies in the fact that hydropower is not only placing pressure on water resources with dam evaporation, the second larger water consuming activity in Brazil, but also that energy supply is suffering from changes in rainfall regimes, with lower dam levels impacting electricity prices and therefore energy access,. Energy supply and electricity capacity expansion fundamentally impact regional socio-economic conditions. Thus, further research should focus on the socio-economic implications of electricity supply expansion through alternative renewable sources. Given that most of the potential for wind and solar power is concentrated in Brazil's least developed region, the Northeast, potential synergies and trade-off with regional socioeconomic development are even more relevant as a pressure point to explore the research agenda emerging from this analysis.

Fuelwood and sugar cane bagasse further pressure water resources from the perspective of irrigation. Hence, energy access policy should take water scarcity into account. An important research focus will be on the complete water cycle impacts on energy supply, not only focused on hydrology projections related to hydropower dam levels.

First generation ethanol is another critical pressure point for sugarcane crop expansion. We therefore call attention to the need for coordinated energy, land use and irrigation policy. This is particularly relevant given the recent change in the water consumption profile of sugarcane crops, from mostly rainfed to mostly irrigated. Future research should therefore focus on the water availability impacts of expanding ethanol use in the transport sector, including impacts over irrigation water availability for other essential food crops.

Although deforestation is known to be critical, and is a clear policy priority for climate change and biodiversity conservation, future research and policy making-should also focus on the interlinkages with water and energy provision. Forest management policy should consider multiple goals: pasturelands, biodiversity conservation, wood production, community livelihoods and water management and energy provision.

Assessments of future scenarios of resource use and governance centred on renewable alternatives to hydropower in the mid to long term would secure energy access with synergies of released pressure on water resources, through food and energy crop irrigation and curbed deforestation. We therefore propose the use of context-specific socioeconomic modelling, or Integrated Assessment Modelling, to assess how changes in resource use practices would impact the achievement of sustainable development in Brazil.

The main limitations of the review encompass excluding non-indexed papers published in Brazil, which are probably statistically representative of Brazilian publications, and a lack of further statistical analysis to test the relevance of each practice in the national context. Further statistical analysis and ‘resource-forcing modelling’ should be performed to enforce this selection and better inform governance and policy for the longer term. This includes modelling scenarios in which resource availability becomes constrained and how different users respond to scarcity.

Finally, we recommend that future studies focus on assessing specifically each of the technology clusters supported by nexus research identified for Brazil. This requires a focus on the governance of affected resources in order to improve the framework for sustainable resource and socioeconomic development. For this purpose, further studies could consider the relevant interlinkages to perform assessments of future scenarios of resource use and governance.

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15 Appendix

All practices analysed, interlinkages and sources

Interlinkage colour code:

Water, energy, food and waste
Waste, energy and food
Water, energy and food
Water, energy and waste
Waste, water and food
Waste and Water
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Water and Energy
Waste and Food
Energy and Food

Water	**Agriculture**	Draining local river basins for irrigation (dripping and aspersion)	Piping or collecting directly from streams and wells for animal consumption	Man-made pond for cattle watering, fish production, irrigation and erosion protection.	Water reuse in dairy cattle farming	Irrigation management through soil water balance (irrigation sensor, critical soil humidity control)	Underground dam	Mini dam for rainwater harvest	Family farming friendly irrigation practices: Bubbler irrigation, superficial irrigation with furrows, plastic canvas by the bed.
	Sources	[55,56,103,126–129]	[103,127,130–132]	[103]	[103]	[103]	[103]	[103]	[103]
	Households	General distribution system (piped)	Artesian well	Cistern - Rainwater harvesting	Collect directly from river/stream/spring	Tank truck	Desalination (Reverse Osmosis Technique - Fresh Water Programme)	Public fountain/cistern	Water Supply System (WSS) - Northeast Semiarid
	Sources	[26,132–134]	[26,135–137]	[14,26,100,101,103,132,133,135,136,138–140]	[26,134,139]	[26,136]	[141]	[139]	[139]
	Treatment	No treatment	Chlorine	Sodium	Calcium hypochlorite	Simplified systems for treatment of water with low-cost technology to meet the immediate demand of rural communities, such as the simplified diffusion chlorinator (plastic vessel - PVC tube or PET bottle).			
	Sources	[132,134,137,142,143]	[137]	[137]	[137]	[137]			

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Waste	**Solid Waste**	Collected	Burnt or buried in the property	Disposed in wasteland	Disposed in river or lake	Recycled	Licenced landfills	Illegal landfills (dumps)	Selective collection	Composting
	Sources	[26,144]	[26,144]	[26]	[26]	[145–147]	[145,147,148]	[148]	[144]	[144,145]
	Effluents/ sewage	Collection system	Septic cesspit	Rudimentary cesspit	Open trench	Directly disposed in river or lake	No sewage system	Decentralized sanitation and reuse (DESAR)	Biodigester cesspit	Integrated system for the treatment of wastewaters (anaerobic unit, subsurface constructed wetlands, photoreactors)
	Sources	[26,133,148]	[26,133,148,149]	[26,133,148,149]	[26]	[26,142]	[26,143,148]	[150]	[103,151,152]	[153]
	Effluents/ sewage (continued)	Decentralised wastewater treatment systems (using coconut husks)	Upflow anaerobic sludge blanket (UASB) for domestic sewage treatment	Bioreactors for effluents from agricultural production	Sewage treatment before disposal in river or lake	Wastewater treatment plants (WWTP)	Constructed wetlands (CW)			
	Sources	[154]	[155]	[156]	[142]	[157]	[157]			
	Agricultural waste	Manure (cattle, swine, goat) biodigester	Pesticide container collection and triple washing of glass and steel containers	Vinasse fertiliser production (from sugarcane)	Reuse of manure for soil fertilising	Runoff water from grain production and residue concetration from confined animal breeding (swine, poultry and dairy)	Chemical fertiliser and pesticide disposal in streams	Various agricultural and forestry waste biodigester	Soap and detergent production from animal waste (pork crackling)	Biomethane production
	Sources	[14,103,106,109,158–162]	[146]	[130]	[14,142]	[142]	[163,164]	[162,165]	[108]	[161]

Energy	**Electricity**	Hydropower (large, with reservoirs, and small)	Wind (centralised and distributed, utility, mini and micro)	Sugar cane bagasse-fired thermal plants - centralised and decentralised/cogeneration plants in sugar cane mills and other agricultural reasidues (babassu nuts)	Wood biomass fired thermal plants (forest waste) - centralised and decentralised	Natural gas fired thermal plants	Oil-fired thermal plants	Oil generators	Solar photovoltaic (decentralised/centralised)
	Sources	[56,63,82,90,92,132,160,166–170]	[56,63,82,90,92,160,166,170–176]	[54,63,82,90,165,170,171,175,176]	[63,82,90,91,160,165,166,177–179]	[63]	[63]	[63]	[14,56,63,89–92,94,166,169,172,174,180–185]
		Manure Biogas	Crop/forest waste biogas	Burnt agricultural waste	Diesel generators	Biodiesel/Palm oil biomass mixed with diesel in generators	Biogas/photovoltaic hybridpower system decentralised - NE Semiarid	Isolated off-grid systems (PV, SHP, biomass)	Hydrokinectic
	Sources	[14,63,103,106–109,158,159,161,162,186]	[107,162,165,178]	[63]	[82,89–92,94,166,170]	[93,169]	[159]	[89–91,170]	[92]
	Thermal energy	Fuelwood (households - coffee, eucalyptus or native forest wood)	Biodiesel, mostly soybeans but also palm oil, sunflower, castor bean etc. including family-farming for biodiesel production	Diesel for transportation	First generation Ethanol	Second generation ethanol (cellulosic, from bagasse)	Liquid Petroleum Gas (LPG) (households)	Biomethane for transportation fuel	Mixed water heating system - solar and electric
	Sources	[26,63,82,159,170,187–191]	[11,54,63,108,111,112,129,166,192,193]	[63]	[11,54,105,194–196]	[105]	[82,160,170,187]	[107,161]	[197]

Food		Extractivism of local nuts, fruits and vegetables	Irrigated sugar cane and soybean crops for energy purposes	Fresh-water irrigated food crops	Treated sewage subsurface drip crop irrigation	Rainfed crops	Bubbler irrigation system for family farming	Integrated fish, poultry and other small animals, small horticulture, hydroponic farming (Sisteminha Embrapa)	Floating cages for fishing	Soil conservation strategies for water maximisation (Human Coexistence with Semi Aridity)	Vinasse fertigation
	Sources	[198]	[54,103,114,129,130]	[55,103,126,127,132,176]	[143,199]	[103,126,130]	[103]	[103]	[103]	[135]	[130,142,199]
		Manured soil/biofertilisers	Direct planting - no ploughing (beans and grains: soybeans, corn, wheat)	Confined cattle/swine-poultry breeding	Family-based dairy farming	Family-based farming beef cattle breeding	Family-based farming horticulture	Family-based fruit farming	Family-based combined/diversified crops/livestock	Chemical fertilisation of soil (Nitrogen, urea, NPK, Ammonium sulphate, Calcium nitrate)	
	Sources	[14,107,108,142,161,163,200,201]	[142]	[142]	[128,131,142,202–210]	[142,202,204,206,208,210,211]	[142,202,206,208,210–213]	[142,202,206,208,210,214]	[142,206,211,215]	[163,201,211,216–220]	
		Pesticide use	Deforestation for new pasture and croplands	Agricultural cooperatives for food and biodiesel plant, ethanol or charcoal production	Small scale firewood production for energy need (Eucalyptus)	Semiconfined Cattle breeding	Extensive cattle breeding	Soil ploughing/tilling (beans and grains)	Direct planting - no ploughing/tilling (beans and grains)	Minimum tillage	Organic farming and Agroecology
	Sources	[163,200,201,219]	[45,103,163,202,221–223]	[111–114,193]	[189]	[14]	[14,221]	[216,217,224,225]	[103,216,217,224]	[216,217,224]	[200,202,206,208,212,225–228]
		Crop rotation/intercropping/fallows/swidden agriculture	Agroforestry systems, Integrated Food, Energy and Environmental Services Production (IFEES)	Family-base native fish aquaculture	Sugarcane/soybean monocropping systems	Extractivism of local nuts, fruits and vegetables	Low Carbon Agriculture[7]	High yield seeds	Mechanisation	Wild animal hunting	Slash and burn
	Sources	[103,200,201,225,226,229]	[114,129,196,212,226,230]	[231]	[221,230]	[198,232–237]	[202,221]	[201]	[201,225]	[226]	[103]

[7] Integrating crop-livestock-forest: recovering degraded pasturelands, treating animal waste.