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Monitoring Brazilian Food Security Based on Emergy Concepts: A Proposed Approach

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Abstract: This study enhances the discussion on food security by examining trade equity between food consumers and the supply chain from an emergy perspective. The objective is to develop a food security indicator for Brazil as a case study that provides a holistic view of the historical relationship (from 1995 to 2022) between the emergy and money received by consumers and the emergy and money supplied by the food chain. Each item in the Brazilian food basket was evaluated using the Emergy Exchange Ratio (EER) indicator, which measures the advantages and disadvantages that consumers and the food chain experience in their exchanges. The results indicate that processed food items such as oils and butter generally provide greater net emergy benefits to consumers compared to fresh food items like meat, bananas, tomatoes, and potatoes, which often favor the supply chain. Furthermore, the findings highlight that vulnerable populations face significant challenges in achieving food security due to their increased efforts to generate income relative to the emergy they receive for their social welfare. The proposed food security indicator reveals that consumers enjoyed a more balanced trade since the mid-1990s; however, this trend has recently begun to reverse, underscoring the need for policies that ensure fairer exchanges. This work contributes to discussions on food security by considering an emergy-based approach with the modified Emergy per Money Ratio (EMR) as a complement to traditionally used approaches.

Keywords: emergy per money ratio; food; fair trade; public policies

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1. Introduction

Food security is a significant challenge in worldwide. In Brazil, according to the latest UN reports [1], 70.3 million citizens face food insecurity, with 21 million Brazilians experiencing severe food insecurity. The most common definition of food security was established by the Food and Agriculture Organization [2] of the United Nations as "Food security involves access by all people at all times to sufficient quantities of nutritious food to lead a healthy and active life". It encompasses four main dimensions: (i) physical availability of food—the supplying of food security, considering factors like food production, stock levels, and net trade; (ii) economic and physical access to food—regarding the incomes, expenditure, markets, and prices to ensure access to food; (iii) food utilization—utilization involves how our bodies make the most of the nutrients in food; and (iv) stability over

time—a guarantee of food access, avoiding periodic access challenges due to factors like adverse weather, political instability, or economic issues.

Food security can only be achieved when the aforementioned dimensions are accessed in an integrated manner [3]. These measures require systematic evaluations based on transdisciplinary, multidimensional, and pluripotent theories and tools that make it possible to integrate the different socioeconomic, cultural and environmental dimensions [4]. According to the scientific literature, psychometric indicators are commonly used to evaluate food security by measuring households' perception of food insecurity [5] (e.g., insufficient caloric intake, child nutrition, or the share of income designated to food expenditures [6]). In Brazil, the Brazilian Household Food Insecurity Measurement Scale (EBIA) is the most commonly used tool to assess household food security [7]. The tool consists of structured interviews (yes or no questions) aimed at investigating the household's food situation. The interview generates a score through which analysts assign a level of food insecurity to the household (mild, moderate, or severe), with scales that vary according to the number of questions [8]. However, the lack of money and other resources [9], as well as the limitations of these indicators in capturing the different dimensions of food security individually [10], prevent the method from being fully applied and hinder the interpretation and understanding of the issue more comprehensively [5]. As a result, multicriteria models have emerged with the aim of capturing household food security through holistic approaches using multidimensional indicators (e.g., the Global Food Security Index (GFSI [11]).

The challenge is to develop comprehensive and systemic indicators to measure food security [12]. With this objective in mind, the goal of this study is to analyze food security through emergy synthesis [13]. According to Odum [13], emergy synthesis is a powerful method for assessing the total energy required in a supply chain (a system) to deliver any product (e.g., food) to the end consumer. In food security studies, emergy synthesis can be particularly useful, as it represents the products (foods) consumed by a person or family and the money spent on their purchase on a common physical basis, called solar emjoules (sej). When both the product and the money are converted to this common basis, it becomes possible to compare the exchange of emergy between different partners in a food chain. By doing so, one can identify whether the exchanges are equitable, i.e., whether none of the partners is benefiting at the expense of the others [14]. The idea is to estimate an equitable exchange between partners, i.e., an exchange in which the amount of emergy received by the consumer (on the demand chain side) in the form of food is equivalent to the emergy received by the seller (on the supply chain side) in the form of money.

This study focuses on proposing a food security indicator considering a historical emergy exchange between consumers and the food supply chain. The goal is to evaluate the exchange of emergy that consumers obtain from purchasing food from the supply chain. The hypothesis behind this reasoning is that if there are imbalances in this indicator, the population may be experiencing food insecurity. For example, if consumers receive low emergy in the form of products compared to the emergy invested in the form of money to buy these products, it indicates an inequitable exchange (i.e., in this case, the seller is benefitting in trading with consumers), which constitutes a situation of food insecurity since access to food is being hindered. By identifying such imbalances, policies can be formulated to ensure fairer compensation, thereby enhancing food security.

The food security indicator proposed and discussed in this study is based on the exchange between families and the market in the purchase of food from a historical series of 27 years (from 1995 to 2022). First, an indicator is estimated for each food item that makes up the Brazilian basic food basket (butter, milk, oil, tomatoes, sugar, wheat flour, bananas, rice, coffee, beans, bread, and potatoes). Next, the combined indicator that covers the entire basic food basket is calculated. These indicators relates (i) the emergy obtained

by the family from the resource in each food and in the Brazilian basic food basket to (ii) the payment in monetary resources for the purchase of the product.

The result is a holistic indicator of food security that can be easily derived from secondary data, making it practical and low cost. Aside from providing discussions based on quantitative data regarding the usage of emergy synthesis as an alternative method for measuring food security, the proposed indicator is estimated for Brazilian populations under three different conditions: (i) for those who earn the Brazilian minimum wage; (ii) for those below the poverty line; and (iii) for those in extreme poverty.

To achieve the initial objectives, a brief review of food security and emergy concepts and definitions are provided, including the interface between them for developing indicators. Next, the proposed new approach/indicator and its key dimensions to measuring food security are outlined. Then, the indicator derived from using emergy as a measurement of food security is shown. Finally, a reflection of the principles and applications of the proposed approach is provided.

2. Definitions and Contextualization of Brazilian Food (In)Security

2.1. Concepts of Food (In)Security

Recent estimates project that the global population is expected to reach approximately 10 billion people by 2050, and as a consequence, this scenario will increase the demand for food [15]. For this reason, one of the greatest global challenges is achieving food security, and the importance of this issue has gained prominence on international agendas, such as SDG 2, which is committed to Zero Hunger and Sustainable Agriculture, with the goal of "ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture".

The World Food Summit (Food Systems Summit—FSS) held in 1996 defined food security as the condition in which people, at all times, have physical and economic access to safe and nutritious food that meets their dietary and nutritional needs. However, the most commonly used definition of food security was established by the Food and Agriculture Organization (FAO) of the United Nations [2], stating that "food security exists when all people, at all times, have access to sufficient, safe, and nutritious food to maintain a healthy and active life".

Based on this last definition, four pillars represent food security: (i) availability—a sufficient quantity of food with an appropriate quality; (ii) accessibility—having sufficient resources (financial or physical) to acquire or exchange food; (iii) utilization—the way households use food through knowledge, skills, and cooking equipment, along with the ability to absorb and metabolize nutrients; and (iv) stability—access to and use of food at all times without facing risks [16]. In summary, food security is multidimensional and must ensure healthy and balanced diets for all people at all times, meaning that all four dimensions must be met simultaneously.

Although different conceptual frameworks shape the understanding of food insecurity, the consequences of this issue present a growing multisectoral challenge globally. This operational complexity undermines political efforts and downplays the severity of the problem, especially in Latin America and the Caribbean [17], Africa [18], and South Asia [19]. In these regions, low levels of education, limited social capital, and low income—as reflected in their GDP per capita—are aggravating factors [17]. With one-third of the global population affected by malnutrition, the implications of food insecurity primarily impact the most vulnerable population groups, who are often underrepresented in food security agendas [20].

2.2. Indicators and Measures of Food Security

Due to the diversity of food security assessments, there is no single consensus regarding its status, whether at the global, national, or household/individual level, as each level requires a series of measures and strategies [21]. In light of the challenges surrounding the issue, various indicators have been developed to address topics such as food availability and access [22], production and utilization [23], supply and trade [24], and the influence of agricultural practices and land use [25].

At the national level, food security indicators include the Global Food Security Index (GFSI) and the Maplecroft Food Security Risk Index, which assess food security based on indicators related to the health status, availability, stability, and access to food; the Global Hunger Index (GHI) developed by the International Food Policy Research Institute (IFPRI) to comprehensively measure and monitor hunger; the Multidimensional Global Poverty Index from the United Nations Development Programme (UNDP), which evaluates the incidence and intensity of poverty; the Global Food Security Index (EIU); and the International Food Security Projection and Assessment from the U.S. Department of Agriculture (USDA). Furthermore, the Food Insecurity Experience Scale (FIES), which consists of questions about people's access to adequate food, is also used.

At the household/individual level, food security measures include the Global Hunger Index (GHI), which is composed of three indicators analyzing the proportion of the undernourished population, the prevalence of underweight, and the mortality rate in children under five years old; the USDA's Household Food Security Monitoring, which uses survey data about food-related behaviors to identify the proportion of the population facing mild to severe food insecurity [26]; the World Food Programme (WFP) of the United Nations includes the Household Food Insecurity Access Scale (HFIAS), which assesses the four domains of food security to classify the severity of insecurity; and the Household Hunger Scale (HHS), which estimates the percentage of households affected by three different levels of hunger severity: (1) little or none; (2) moderate hunger; and (3) severe hunger. The Household Dietary Diversity Scale (HDDS) measures the number of different food groups consumed over a specific reference period and the Coping Strategies Index (CSI), which evaluates households' behaviors and examines how they cope with food shortages.

Although there are options, selecting individual indicators to evaluate all facets of food security is not an easy task [27], particularly because there are diverse pieces of information that may fail to capture psychological factors such as anxiety and concerns [26]. Therefore, national and international agencies have developed or adjusted food security indicators that can be applied to individual nations or in the global context. Adapted from the U.S. Household Food Security Survey Module (US HFSSM), the Brazilian Scale for Measuring Household Food Insecurity (EBIA) is a tool for assessing household food insecurity (FI) in Brazil [7]. The EBIA uses four different categories (food security, mild food insecurity, moderate food insecurity, and severe food insecurity) to classify households based on the severity level of FI [3]. The EBIA aids in monitoring and improving national public policies to promote food security, as it considers, in addition to psychometric analyses, concerns about the ability to acquire food due to limited resources, the low variety and quality of the diet, and restrictions on food intake by first surveying adults and children subsequently, when applicable, which allows for identifying households that exhibit moderate and severe degrees of food insecurity [28].

Although there are various and important indicators at different levels with the primary goal of measuring and making decisions to guarantee food security, none of these approaches and their indicators capture the exchange capacity (selling and buying) between consumers and food suppliers from a biophysical perspective. Although there are various and important indicators at different levels with the primary goals of measuring and

making decisions to guarantee food security, none of these approaches and their indicators capture the exchange capacity (both buying and selling) between consumers and food providers from a biophysical perspective. Economic approaches exist, are commonly used, and hold their importance, but they lack greater objectivity in better understanding, in a systemic way, food access across different social levels, which have varying capacities to acquire food. In this regard, emergy synthesis appears as a potential tool, as presented in the following section.

2.3. Emergy Assessment and the Four Dimensions of Food Security

The imbalance between the supply and demand for food resources is a critical issue in many countries, whether in terms of availability, accessibility, utilization, or stability. Thus, understanding the combined actions of these factors from the perspective of space–time evolution is an important basis for comprehending the global pattern of food security [29]. The use of emergy synthesis seeks to capture various key components that influence differences in the performance of systems, thereby presenting a new perspective in studies on food (in)security.

Some research has linked food production and consumption patterns by employing emergy synthesis to explore the maintenance of agroecosystems [30] and assess the sustainability of such systems. For instance, Skaf et al. [31] explored food security and sustainable agriculture in Lebanon, while Mwamboo et al. [32] applied emergy synthesis to evaluate corn cultivation in Ghana.

The literature indicates that food availability is directly related to production, distribution, and trade, which in turn must be interconnected with an efficient agricultural and livestock cropping system. Regarding this, Golshani et al. [33] verified, through the emergy method, that an integrated crop–livestock system not only has the capacity to reduce economic risks and increase profitability but can also provide significant environmental benefits, and has enormous potential to increase food availability. Other production systems have also been investigated using emergy synthesis, such as the dairy production chain [34], integrated production of grains, pigs, and fish [35], as well as the nexus of water, energy, and food [36], among others. All these studies provided important subsidies for formulating public policies to increase food availability.

Food accessibility, in addition to being a multi-scale socio-ecological challenge, must provide access to healthy and nutritious food. Authors like Narayan and Jayakumar [37], with the help of an emergy model, argue that cities need to produce their own food because global projections indicate that the demand for water, energy, and food will significantly increase in the coming decades, which will hinder food accessibility [36].

Emergy accounting can also be used to measure food utilization, as this pillar is clearly linked to the issue of nutritious food that must meet dietary needs. Some research, such as that conducted by Cristiano [38], reported that vegetarian diets reduce the total emergy required for food production, while Allegretti et al. [39] performed an emergy assessment of insect flour as an alternative feed source for the Brazilian poultry industry. These studies highlight the importance of emphasizing the nutritional and dietary components of food security, as well as of promoting sustainable consumption.

Finally, stability is related to the stable process of feeding over time and that this process is not negatively affected by natural, social, economic, or political factors. From ecological and economic perspectives, Lu and Campbell [40] studied the balance between the emergy delivered to markets in agricultural products (such as fish, pork, and vegetables) and the purchasing power of consumers, finding that the emergy of the money was less than the emergy contained in food production. Skaf et al. [31] compared different food cultivation systems using emergy and proposed a set of environmental and socio-economic

indicators aimed at facilitating access to safe, healthy, and nutritious food as a tool for improving food security. These studies indicated that food production and consumption are affected by economic, social, and ecological factors, providing scientific support for sustainable production and consumption strategies.

The literature shows that the emergy synthesis method has been used to evaluate aspects related to food security. Even though it is somewhat diluted in relation to the four dimensions of environmental security, the method proves to have great potential due to its characteristics, including different types of energy quality, the value quantified from the perspective of the donor side, and the energy memory of the generated resources. These characteristics differentiate it from other methods, complementing analyses for more effective decision-making.

3. Materials and Methods

The approach proposed in this study investigate household food security by evaluating the advantages and disadvantages in the exchanges between the purchaser (households) and the food supply chain. The study is based on the assumptions of inequitable trades, as observed by Odum [13], between wealthy (primarily urban) and poorer (primarily rural) countries using the Emergy Exchange Ratio (EER) as main indicator. It is suggested that, just like rural states, poorer families exert greater effort to generate currency than richer families according to their emergy/money ratio. Understanding the advantages of emergy synthesis in relation to other methods for discussing food security, this method is considered in this study.

3.1. Emergy Accounting, Its Synthesis, and Transformities

Emergy accounting is an environmentally oriented method that advocates the existence of an energy hierarchy in qualitative aspects. This hierarchy starts with sunlight energy, the most abundant, wide-spread, and low-quality energy. Conceptually, emergy is defined as the available energy, previously used directly and indirectly, to obtain a product or service in a particular process [13,41,42]. In turn, emergy synthesis is a methodological approach that accounts for the contributions of nature (renewable and non-renewable natural resources) and the economy (financial resources) in a common metric, the solar emjoules (sej), which distinguish it from the joule (J) and point out a different quality evaluation based on a donor-side point of view, i.e., the effort of nature in making available a resource quantified from a biophysical perspective. As an emergy synthesis result, the solar emjoule is expressed per metric unit or energy content of a product (output flow), being called 'transformity (Tr)'; currently, the Unit Emergy Value (UEV) is the general term applied to any sej per unit ratio, including energy, mass, and others. From a hierarchical chain, each process transformation in a system aggregates more energy to the output, increasing its energy quality, as expressed by its UEV [13,43]. Thus, emergy synthesis is always conducted using Unit Emergy Values (UEVs in sej/unit) and other factors determined relative to a specific planetary baseline [13,43]. The aim here is not to provide all the theoretical details behind emergy synthesis; therefore, it is suggested to refer to other works for more details, particularly the one by H.T. Odum [13].

3.2. Food Security Indicator Based on Emergy

Odum [13] suggests that, to assess equity in exchanges between buyers and sellers, the proposed models and indicators should be measured in emergy. By definition, the Emergy Exchange Ratio (EER) is the ratio of emergy exchanged in a trade or purchase (what is received to what is given), measuring the relative trade advantage of one partner over the other [41], as shown in Equation (1) in Figure 1. There are four pathways involved in

emergy exchange, two in each direction (two flows of products and services, and two flows of money paid) [13], which help in proposing the indicator. In this study, the exchanges occur between the food products received by the families and what they paid for their acquisition (Table S1).

$$Emergy\ exchange\ ratio_{household} = \frac{Emergy\ received_{product}}{Emergy\ delivered_{money}} \quad (1)$$

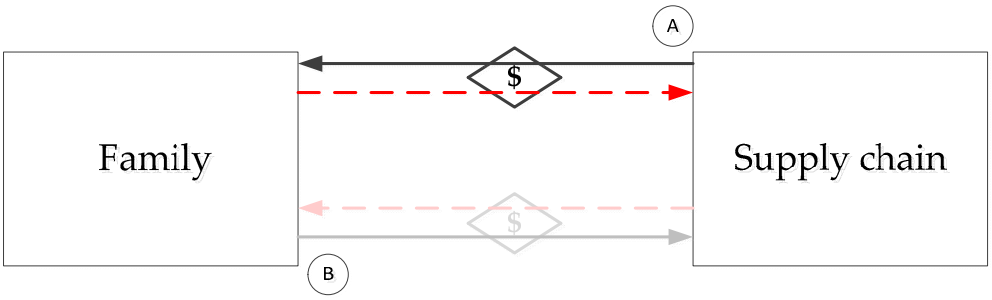

Figure 1. Emergy Exchange Ratio for evaluating the benefits of purchases and sales: A—the flow of products and services provided by the market and paid for by families; and B—the flow of services (as a product) provided by families and paid in currency by the market. Please see Supplementary Material A for more details on emergy synthesis and its EER index. Source: adapted from Odum [12].

Emergy received refers to the emergy received by the buyer in the form of food items. In this study, the buyer is defined as a family, and the product is defined as the food items included in the basic food basket. Emergy delivered refers to the emergy paid for the acquisition of the product in the form of money.

3.2.1. Emergy Received in Product Form: The Emergy of the Food Basket

First, the emergy received was obtained for each food item for each year ($\forall_{year}$). Then, the emergy received for each food item was added to estimate the emergy for the food basket. Therefore, Equation (2a) suggests the annual emergy received from the food basket when considering a family with four people, as usually considered in social statistics.

$$Emergy\ received_{product} = \sum_{i=1,2...12}^{n} Emergy_{Food}\ \forall_{year} \quad (2a)$$

$$Emergy_{Food} = Emergy_i \times FA_i \times 4184 \times UEV_i\ \forall_{year} \quad (2b)$$

$$FA_i = Estimated_{FA_i} \times 4\ \forall_{year} \quad (2c)$$

where $Emergy\ received_{product}$ is the emergy provided from the food basket acquisition for an average Brazilian family (sej/yr) for each year ($\forall_{year}$). The emergy from the food basket is the sum of the emergy provided for each food item; $Emergy_{Food}$ is the emergy provided from each food item acquisition for an average Brazilian family (sej/yr) for each year ($\forall_{year}$); $Energy_i$ is the energy (kcal/g) for each food i; FA is the total estimated food aquisition per family (g/yr) for each food i; 4184 J to kcal; UEV is the Unit Emergy Value of the food item i; $Estimated_{FA_i}$ is the estimated food item acquisition (g/person.yr) of each food i; and 4 is the average number of persons per family.

The selected food items were comprised in the food basket and determined according to the methodological guidelines of the Inter-Union Department of Statistics and Socioeconomic Studies (DIEESE) [44]. Then, the food items were divided in three categories [45] as follows: (i) in natura (meat, potatoes, tomatoes, and bananas); (ii) minimally processed (milk, beans, rice, wheat (flour), and coffee (powder)); and (iii) processed (bread, sugar,

lard/oil, and butter). The quantity of each food item ($Estimated_{FA_i}$) was estimated using raw data from the Household Budget Survey [46], considering food acquisitions in the years 1987, 1995, 2002, 2008, and 2018. Subsequently, an annual estimate of food acquisition evolution was generated using a polynomial equation for the period from 1995 to 2022. The criteria for the adoption of the polynomial equation were $p < 0.05$ and a higher R^2 than the other estimated models.

In the next step, food acquisition was estimated in kcal/yr by multiplying the energy content by the quantity for each food item ($Energy_i \times FA_i \times 4184$) and converting to J. The energy content of each food item was obtained from Tabela Brasileira de Composição de Alimentos [47] (kcal/g).

Finally, the emergy for each food item ($Emergy_{Food}$) was obtained multiplying the food acquisition (in J/yr) by the UEV (in sej/J) for each food item. The UEVs were obtained from the scientific literature as follows: meat, milk, beans, rice, potatoes, tomatoes, sugar, and butter [48]; wheat (flour) and bread [49]; coffee (powder [14]); bananas [50]; and lard/oil [51]. The UEVs were adjusted to the emergy baseline proposed by Brown et al. [52] of 12.0×10^{24} seJ/J (Tables S2 and S3).

3.2.2. Emergy Delivered in Payment Form: The Household Emergy/Money Ratio

The emergy delivered for the food acquisition in money form for each year ($\forall_{year}$) was estimated for each food item using Equation (3a). Basically, the emergy delivered in money form was obtained by multiplying the household emergy/money ratio ($EMR_{household}$) for each household income by the estimated payment for the acquisition of each food item.

$$Emergy\ delivered_{money} = EMR_{household} \times FP_i\ \forall_{year} \quad (3a)$$

$$FP_i = Estimated_{FP_i} \times FA_i\ \forall_{year} \quad (3b)$$

where $EMR_{household}$ represents the ratio between the emergy used per family (sej/yr) and household income (BRL/yr); FP_i is the total estimated payment for the acquisition of each food item i (BRL/yr); $Estimated_{FP_i}$ refers to the estimated market price (BRL/g) for each food item i; and FA is the total estimated food acquired per family (g/yr) for each food item i.

The $EMR_{household}$ is proposed as the ratio between the emergy required for social welfare—including food, electricity, natural gas, solid waste treatment services, and environmental resources—and the household income received (Figure S1). The $EMR_{household}$ was estimated as shown in Equation (4).

$$EMR_{household} = \frac{Emergy_{family}}{wage_{family}}\ \forall_{year} \quad (4)$$

where $Emergy_{family}$ is the minimal emergy requirements necessary for human welfare, encompassing food, natural gas, electric power, and environmental resources, calculated at 47.17×10^{13} sej/person·year [53]) and multiplied by the average household size of four members. The emergy contribution to solid waste treatment is 298.31×10^{13} sej/yr for the family. It was not included the emergy provided by formal education and information, since both emergy flows are often not found in vulnerable populations [54]; $wage_{family}$ is the Brazilian minimum wage (in BRL/yr) paid from 1995 to 2022 [55,56].

In this study, the $EMR_{household}$ represents the ratio between the emergy used per family (sej/yr; $Emergy_{family}$) and household income (BRL/yr; $wage_{family}$). The $EMR_{household}$ is estimated for five household income ranges based on information from IBGE and World Bank for poverty and extreme poverty, measured in purchasing power parity (PPP) at 2017 international prices [57], and updated according to the World Bank in 2022. The values used

were USD 1.90 per day for extreme poverty and USD 5.50 per day for poverty. In addition, three other household income ranges are suggested to contrast the net emergy benefits in trades among households categorized. The five household income ranges are as follows: (i) percentile 60, corresponding to a household income of one minimum wage per month; (ii) poverty line, corresponding to a household income of half a minimum wage per month; (iii) extreme poverty line, corresponding to a household income of one-fifth of a minimum wage per month; (iv) percentile 90, corresponding to a household income of 2.6 times the minimum wage per month; and (v) percentile 80, corresponding to a household income of 1.6 times the minimum wage per month. The $EMR_{household}$ equation for each household income range can be found in Supplementary Material A, Table S4.

In turn, the annual estimated food acquisition evolution (FA_i) is suggested by following the earlier steps showed in the previous subsection. As well as the selected food items, the nominal prices paid per kilogram for each food item are also obtained from the DIEESE database [44] and from the other specialized literature in a time window from 1995 to 2022. An estimated historical series of nominal prices ($Estimated_{FP_i}$) is considered according to the average price for each food items across 17 capitals in Brazilian states [44]. Then, a historical series of nominal prices was estimated using an exponential equation. The criteria for the adoption of the exponential equation were $p < 0.05$ and a higher R^2 than the other estimated models. Finally, the estimated payment for the acquisition of each food item (FP_i) was obtained by multiplying the historical series of nominal prices by the annual estimated food acquisition for each food item (Table S5).

3.3. Multiple Correspondence Analysis (MCA)

The associations among exchange equity, food categories, and household income were evaluated using the MCA method. The MCA is an unsupervised machine learning technique employed as an exploratory statistical method. This multivariate analysis technique enables the examination of associations among more than two categorical variables, as well as the intensity of these associations. In essence, MCA reduces the dimensionality of categorical data, allowing for the identification of patterns and relationships between the variables studied [58].

MCA provides a valuable tool for data exploration and visualization. Identifying the relationships between exchange equity, food categories, and household income makes easier to identify and discuss the inferences on which food groups may require greater emphasis in the formulation of public policies aimed at reducing food insecurity among the most vulnerable populations.

The method for applying the MCA considers the data obtained from the previous subsections. The MCA algorithm was programmed in Python 3.11, employing the NumPy and Pandas libraries for mathematical operations and data manipulation, and SciPy for data normalization and unsupervised clustering algorithms, besides using Matplotlib (v3.8.2) and Seaborn (v0.12.2) for visualization. All software components are licensed for free use.

4. Results and Discussion

4.1. Behavior of the Emergy Exchange Ratio for Food Acquisition

Figure 2 presents the exchanges measured using the EER between consumers and the supply chain for each food item, focusing on demonstrating the trades for a household income of one minimum wage per month. According to the results, three distinct behaviors can be observed regarding the evolution of exchange equity: (a) exchanges beneficial for consumers (e.g., bread, milk, oil, coffee, and butter); (b) exchanges beneficial for the supply chain (e.g., beans, meat, bananas, flour, tomatoes, and potatoes); and (c) exchanges with oscillating beneficiaries (e.g., rice and sugar).

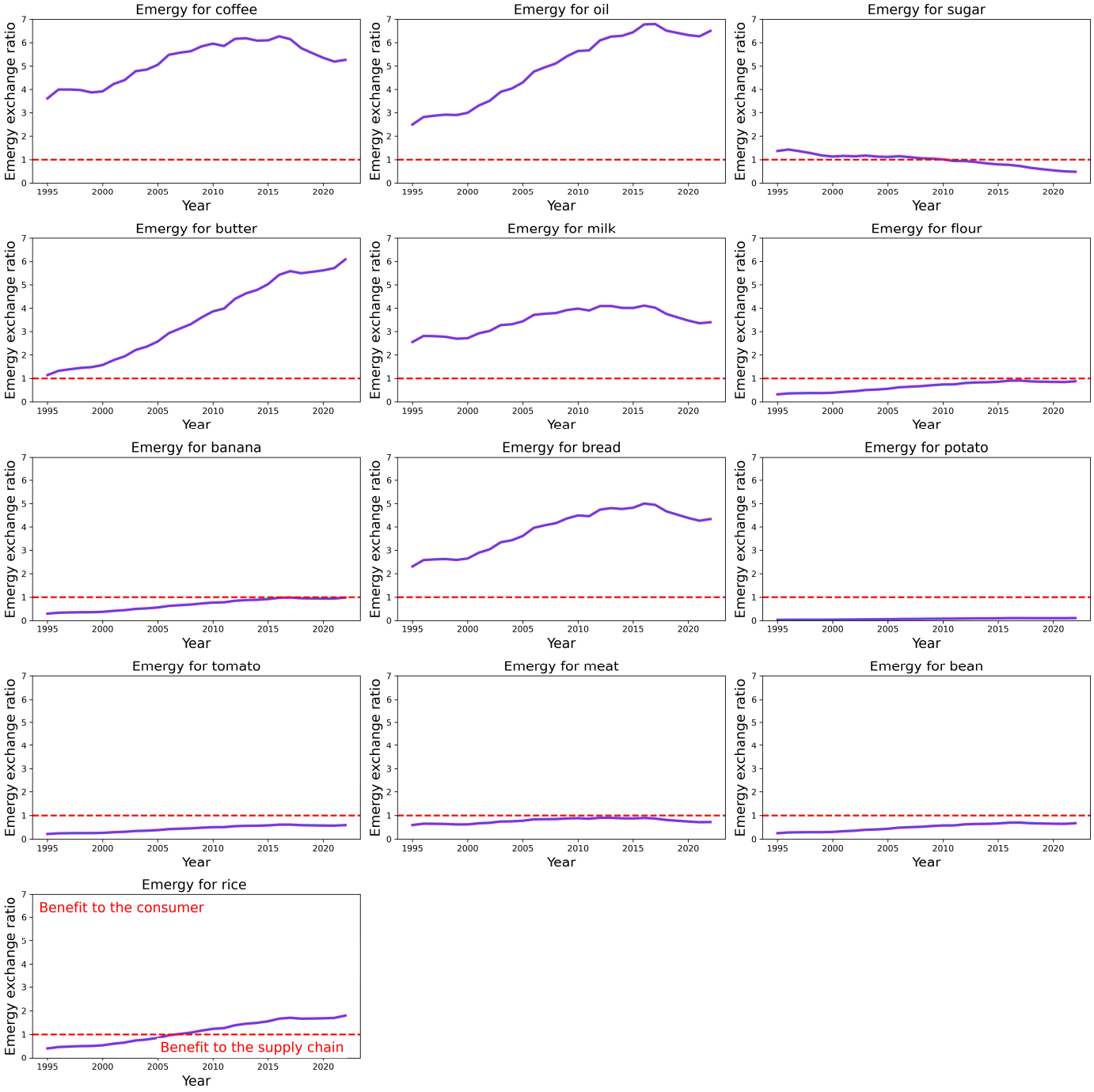

Figure 2. The emergy benefit in food acquisition for families earning a minimum wage. The emergy benefit in food acquisition for those earning a minimum wage per month was calculated by comparing the emergy of the product to the emergy expended in monetary form for its acquisition. The emergy of the product was obtained from Equation (2b): Energy content of the product (kcal/g) × food acquisition (g/yr) × 4184 J × Unit Emergy Value (sej/J). Both the UEV and the energy content of the product were sourced from the scientific literature. The emergy expended in monetary form for product acquisition was calculated using: Emergy-to-Money Ratio (EMR) (sej/$) × food acquisition (kg/yr) × price (BRL/kg). The EMR, a microeconomic metric, was proposed by considering the relationship between the emergy required for the livelihood and the income earned as wages. The emergy for the livelihood encompassed both the nutritional energy requirements and the environmental emergy flows, as described by Nacimento et al. [53]. The annual wage was considered the sole source of household income, with yearly variations from 1995 to 2022 based on IBGE data. The

food acquisition data were sourced from the metadata of the Pesquisa de Orçamento Familiar [46], covering food acquisition in the years 1987, 1995, 2002, 2008, and 2018. A polynomial equation was used to fill in the years with missing data, as previously described in the Section 3. The nominal price paid per kilogram of food was obtained from Departamento Intersindical de Estatística e Estudos Socioeconômicos (DIEESE) reports, which considered the average annual price of food items in the basic food basket for 17 state capitals in Brazil [44]. Please see Supplementary Material A for more details about the calculation memory, Table S1.

According to the results, beneficial exchanges for consumers suggest that more emergy was acquired with less money flow for the acquisition of food items and vice versa. The quantity purchased and the UEV adopted result in more advantageous exchanges for those who purchase the food items. In other words, the more product purchased and the greater the UEV of the food item, the more advantageous the exchange will be for the consumer. For food items, the UEV is strictly related to both the production of the food at farm level and its processing phase. In this sense, more processed products tend to have a higher UEV (e.g., butter, coffee powder, and bread; Table S2). On the other hand, another factor that impacts trade is the practiced price for food items. As an example, for the exchanges for sugar, a higher value was observed for its annual growth rate of the exponential equation in the annual price evolution. In other words, the increase in the annual price of sugar and the reduction in the acquisition of the product by consumers become disadvantageous for its trade over the years, which may explain the downward behavior of the trade.

Figure 3 presents the evolution of exchanges between consumers and the supply chain, based on the EER, for the acquisition of the food basket according to the household income. The figure shows the grouped behavior of food item acquisition, considering how exchanges evolved over the time window evaluated. The results show an ascending trend in the trade-offs between food items and money flow that was favorable to consumers until mid-2015, when the trade-offs started to fall, becoming disadvantageous for the poverty line, which had advantageous trade-offs from mid-2003 to mid-2015. This behavior suggests that from mid-2015 onwards, consumers had to spend more emergy (in monetary form) to obtain food items than before, reaching a level of exchange similar to mid-2003. It can also be seen that exchanges for an extreme poverty household income were less affected than for other family incomes, which were always at a disadvantage in exchanges. It is possible to suggest that this behavior is due to the greater effort made by people in conditions of extreme poverty to generate one Brazilian Real (BRL), making exchanges for this income range always disadvantageous [13]. On the other hand, beneficial exchanges for consumers suggest that more emergy was acquired with less money flow for the acquisition of food items and vice versa. In addition, the quantity purchased and the UEV adopted boost more advantageous exchanges for those who purchase the food items. Also, it can be observed that for a minimum wage household income, the advantages obtained from exchanges involving bread, oil, coffee, butter, and milk allowed for beneficial exchanges for consumers throughout the observation period. This behavior was not observed for households at the poverty line and extreme poverty levels, which experienced longer periods of disadvantageous exchanges.

Another aspect of Figure 3 that deserves attention is the oscillating behavior in exchanges between consumers and the supply chain across all curves. Notable is the inflection point in the curve in 2002, which indicates a more pronounced advantage for consumers in acquiring the basic food basket; additionally, there is a decreasing trend in the curves starting from 2016, suggesting a greater balance in exchanges that favor the supply chain. Since the 1990s, Brazil has undergone significant transformations in public policies related to food security and hunger. The country's trajectory in addressing hunger is marked by innovative governance strategies and social policies that have garnered international

recognition, yet it also faces challenges that have resurfaced in recent years due to political and economic shifts. The 1990s in Brazil were a time of democratic transition, marked by the 1988 Constitution and various reforms. From 1995–2002, economic policies focused on inflation control, currency stabilization with the Real Plan, and opening the economy. While these reforms stabilized the economy, they also worsened inequality and led to cuts in social programs, impacting food security [59]. Government efforts, like the Basic Food Basket Program, were criticized for being reactive and not addressing structural issues like poverty. However, even in this context, food insecurity decreased, as measured by different approaches, as well by the emergy approach [60] (Figure 3), culminating in the first half of the following decade.

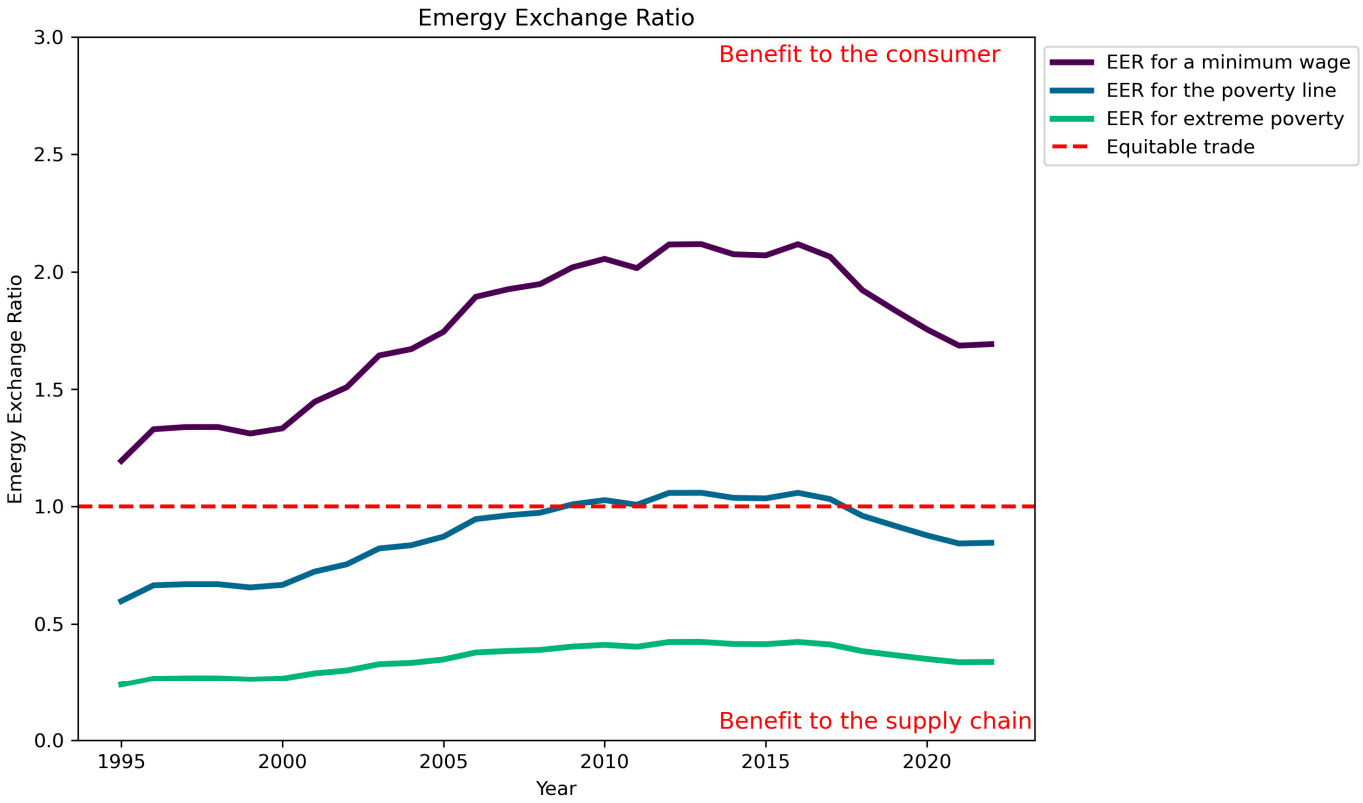

Figure 3. Comparison of Emergy Exchange Ratios (EER) for basic food basket acquisition based on the family income. The emergy benefit in food acquisition for those earning a minimum wage per month was calculated by comparing the emergy of the product to the emergy expended in monetary form for its acquisition. The emergy of the product was derived from the following formula: Energy content of the product (kcal/g) × food acquisition (g/yr) × 4184 J × Unit Emergy Value (sej/J). Both the UEV and the energy content of the product were sourced from the scientific literature. The emergy expended in monetary form for product acquisition was calculated using: Emergy-to-Money Ratio (EMR) (sej/$) × food acquisition (kg/yr) × price (BRL/kg). The EMR, a microeconomic metric, was proposed by considering the relationship between the emergy required for the livelihood and the income earned as wages. The emergy for the livelihood encompassed both the nutritional energy requirements and the environmental emergy flows, as described by Nacimento et al. [53]. The annual wage was considered the sole source of household income, with yearly variations from 1995 to 2022 based on IBGE data. The food acquisition data were sourced from the metadata of the Pesquisa de Orçamento Familiar [46], covering food acquisition in the years 1987, 1995, 2002, 2008, and 2018. A polynomial equation was used to fill in the years with missing data, as previously described in the Section 3. The nominal price paid per kilogram of food was obtained from Departamento Intersindical de Estatística e Estudos Socioeconômicos (DIEESE) reports, which considered the average annual price of food items in the basic food basket for 17 state capitals in Brazil [44]. Please see Supplementary Material A for more details about the calculation memory, Table S1.

A turning point in Brazil's fight against hunger came in 2003, which launched a series of groundbreaking social policies that directly addressed food insecurity through a multi-dimensional approach. The most notable program was "Fome Zero" (Zero Hunger), which integrated various initiatives aimed at addressing both the immediate needs of the hungry and the structural causes of poverty. This program sought to improve access to food, promote sustainable agriculture, and provide cash transfers to poor households. It was built on both cash transfers (via another program named "Bolsa Família") targeted at families in situations of poverty and extreme poverty [61] and broader development strategies, including nutrition, agricultural support, and income redistribution. During this period, the Organic Law of Food and Nutritional Security (LOSAN) was also implemented, and the National Council for Food and Nutritional Security (CONSEA) was created, allowing for more efficient coordination among government, civil society, and academia in the formulation of food security policies [62]. While the early 2000s saw gains in reducing hunger, the post period of 2010–2012 was characterized by economic instability and political crises, which began to erode the gains made in food security (this is also seen in Figure 3). Cuts in social spending, mainly caused by the low economic growth, undermined the state's capacity to further expand or even maintain its social programs, leading to increased vulnerability among poor households. Since 2016, a period marked by fiscal austerity and cuts in social programs such as the Bolsa Familia Program and PRONAF (a program focused on supporting family agriculture), which had been central to the reduction of hunger and poverty in the previous decade, undermined the gains obtained in the previous period.

From an overall analysis, different methods have been used to analyze food security or insecurity with a priority focus on economic issues, while environmental performance has been little explored [63]. To reduce this gap and consider the impact that economic factors impose on ecosystems, emergy synthesis proposed by Odum [13] was applied because it considers quantitative and qualitative parameters of the available energy used to discuss sustainability issues [64]. For Narayan and Jayakumar [37], environmental accounting in emergy establishes a strong link between food systems and social, economic, and ecological aspects, and this can be a valuable approach to identifying unsustainable patterns. In particular, emergy synthesis also conveys a wide range of easily understandable information to policy makers, producers, and consumers, and this contributes significantly to the effectiveness of policies on food security.

4.2. Insights into Exchanges Based on Food and Family Income Classes

The MCA is an unsupervised machine learning technique that is used to analyze the similarity between categories based on the χ^2 distance. It is an exploratory factor analysis technique for multivariate categorical data that describes the structure of associations between a group of categorical variables, as well as the similarities and differences between the individuals to which those variables apply [65]. In addition, the MCA transforms the original variables (categories) into a smaller number of new synthetic variables, called principal components or dimensions. The principal components (or principal dimensions; Dim. 1, and Dim. 2) are shown on the x and y axes, respectively. These dimensions summarize the underlying structure of categorical data, seeking to project the data into a reduced dimensional space that allows key patterns or associations to be highlighted [66]. In this study, Dim. 1 is more closely related to the equity of trades, while Dim. 2 is related to household income (Figure 4). Together, the variables help explain 39% of the variance in the data, in which Dim. 1 accounts for 23.95% of the total variance in the data and Dim. 2 accounts for 15.37% of the total variance in the data. It is also possible to observe the formation of four quadrants (Q). These are formed according to the negative and positive values shown on the axes, in which Q1 (top right) shows positive variations for both

dimensions; Q2 (top left) shows negative variations for Dim. 1 and positive variations for Dim. 2; Q3 (bottom left) shows negative values for both dimensions; and Q4 (top left) shows Dim. 1 with positive values and Dim. 2 with negative values. More clearly, the points in Q1 and Q4 are more related to advantageous exchanges, while Q2 and Q3 suggest disadvantageous exchanges. Q1 refers to household incomes of a minimum wage; Q2 refers to extreme poverty household incomes; Q3 refers to poverty line household incomes; and Q4 refers to people earning 2.7 times the minimum wage household incomes (percentile 90). Thus, the association highlighted by the proximity of the points suggest a disadvantageous Emergy Exchange Ratio (EER) for people in extreme poverty and poverty and an advantageous EER for families with an income of 2.7 times the minimum wage and minimum wage household income. This suggests that families in poverty and extreme poverty need to exert significantly more effort to generate the equivalent of one dollar compared to families with higher financial resources.

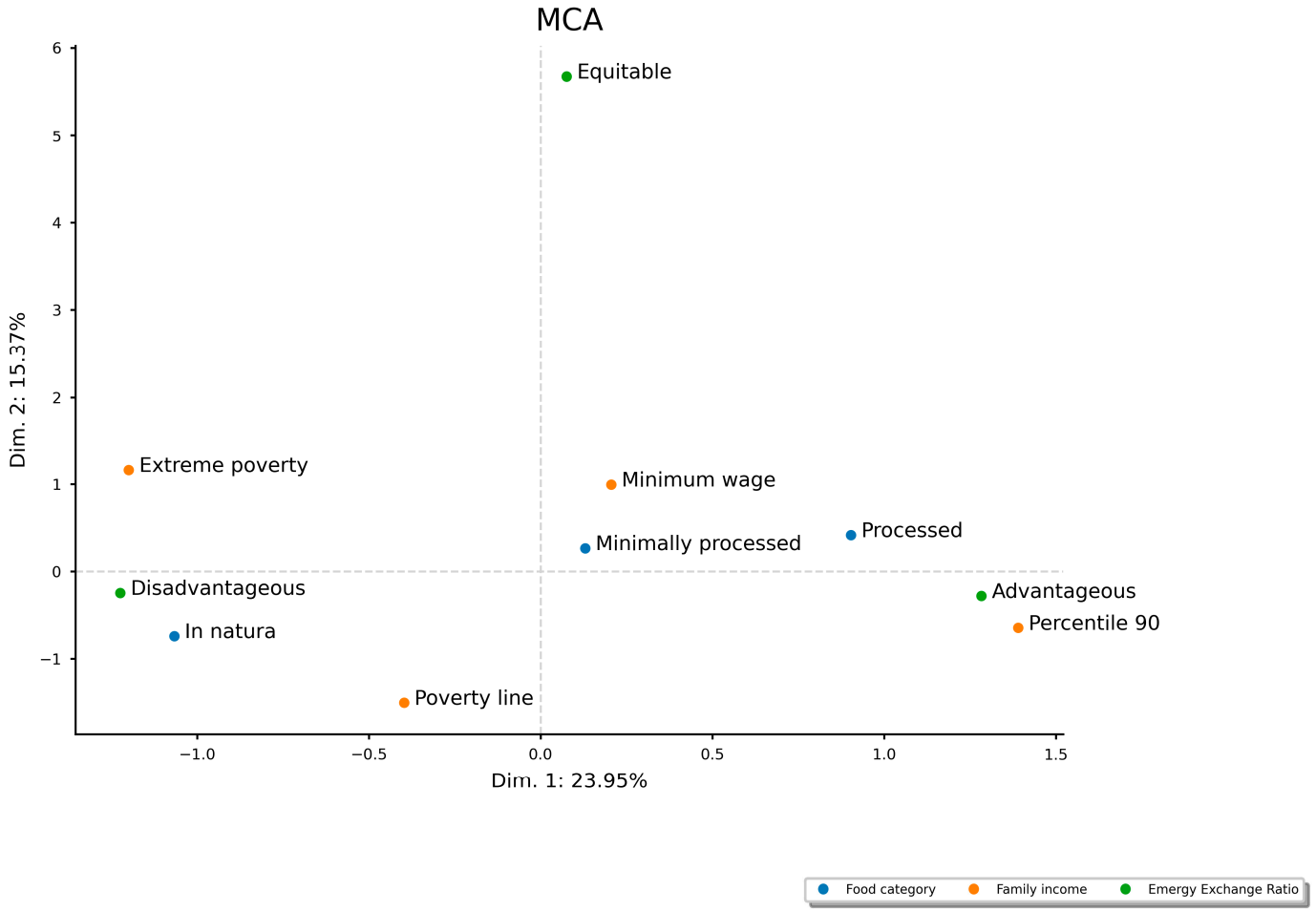

Figure 4. Perceptual map from the multiple correspondence analysis (MCA) illustrating the relationships between food categories, family income levels, and Emergy Exchange Ratio classifications. Note: The food classes were (01) in natura (meat, bananas, potatoes, and tomatoes); (02) minimally processed (milk, flour, rice, beans, and coffee); and (03) processed (sugar, bread, butter, and oil/lard). The income classes were (01) extreme poverty (families with 1/5 of a minimum wage/month); (02) minimum wage (families that receive a minimum wage/month); (03) poverty line (families with 1/2 of a minimum wage/month); and (04) percentile 90 (families that receive 2.7 times a minimum wage/month). For the "Emergy Exchange Ratio—ERR", three classes were considered: (01) EER < 0.9—characterized by unfavorable consumer exchanges with the supply chain; (02) 0.9 < EER < 1.1—characterized by an equitable trade between consumers and the supply chain; and (03) EER > 1.1—characterized by favorable consumer exchanges with the supply chain.

In addition, it is observed that in natura food items (bananas, meat, potatoes, and tomatoes) were more associated with disadvantageous exchanges, while processed food items (sugar, bread, oil/lard, and butter) were more associated with advantageous exchanges. Perhaps, this is an explanation for why people with lower purchasing power tend to buy highly processed foods, which are often considered unhealthy. In natura food items are characterized by being less processed and, therefore, having lower UEVs when compared to processed food items [48]. Thus, the more advantageous exchanges between the emergy of money and the emergy of processed food items could be obtained from processed food acquisition. Secondly, exchanges among poorer families will sometimes be more disadvantageous than families above the poverty line when acquiring food items since families in extreme poverty and poverty exert greater effort to generate wealth. Moreover, it can be suggested that the disadvantages arising from exchanges made to acquire in natura food items hinder the potential benefits of exchanges for processed products, preventing them from balancing the overall value when considering the combined group of foods (food basket). However, ultra-processed food consumption should be limited due its relation with health problems [67]. As an alternative to acquiring ultra-processed industrialized foods to balance the trade-offs in food acquisition for vulnerable populations, indirect forms of processing—focused on local food production and supply—may create a more equitable food exchange for these groups. For example, since cooking and preparing food is a form of processing that enhances product quality (measured in nutritional value), public policies that promote the provision of complete and nutritious meals by solidarity restaurants could ensure a fairer exchange in food acquisition for people in situations of social vulnerability. To this, the expansion of initiatives such as community restaurants, which offer low-cost meals, ensuring both quality food and support for the local economy would be more easily implemented. It would also be beneficial to create/expand a robust food security network that integrates food banks, donations, and distribution in vulnerable communities, ensuring that no individual goes hungry.

Making exchanges more favorable and equitable, particularly in the context of the economic imbalances, is a complex and multifaceted task. However, there are potential solutions and recommendations for actions that can be implemented across long and medium time horizons:

- Long-Term—The most straightforward solution is to increase the income of the poorest ones and reduce population inequality. Investing in education and professional training programs to enhance the population's skills can significantly boost employability and lead to higher earnings. A complementary option would be to promote tax reforms that reduce the burden on low-income groups while increasing it for the wealthiest, contributing to a fairer distribution of resources. Additionally, it would be prudent to implement policies that protect workers in vulnerable sectors, ensuring their rights and access to essential benefits.
- Medium-Term—Stimulating local production by creating subsidies for local farmers who produce essential foods, especially those sold fresh, could be achieved by including technical assistance, access to inputs, and tax incentives. However, it is important to consider community participation and awareness campaigns about the importance of healthy and local food, linking this to fresh produce fairs and even cooking classes. Similarly, it would be beneficial to support urban and community gardens with funding and resources and to form partnerships with schools and community organizations to promote food production. Finally, it would be necessary to strengthen public policies by expanding the reach and investment in food acquisition programs, ensuring that small producers have a market for their products and that vulnerable populations have access to food.

These actions, when implemented together, can contribute to the creation of a system of exchanges that is fairer, more balanced, and sustainable for all involved. However, it is important to emphasize that these suggestions, if applied, should be subjected to a monitoring and evaluation system to ensure they achieve the proposed objectives and can be adjusted as necessary. This will allow for an adaptive model that responds to the constantly changing social and economic dynamics.

5. Conclusions

This study seeks to enhance the discussion on food security by assessing the trade equity between consumers and the food supply chain using emergy indicators. Thus, the study innovates by bringing to the discussion the use of indicators that consider the environmental contribution (donor side) to food security. This fact highlights the understanding of the bottlenecks that permeate food security as things that are multisystemic and multidisciplinary.

By employing the Exchange Emergy Ratio (EER), the findings reveal that processed food items (sugar, bread, oil/lard, and butter) offer greater benefits to consumers, whereas in natura food items (including meat, bananas, tomatoes, and potatoes) disproportionately favor the supply chain, which highlights a significant disparity in the distribution of benefits. Regarding trade equity within the food basket, the findings reveal that families living below the poverty line face disadvantageous trade conditions, significantly hindering their access to essential food items, and suggesting a greater effort by people on the poverty line and in extreme poverty to generate money. This finding highlights the need to promote public policies that guarantee equity in trade in food acquisition for people in situations of social vulnerability.

Both the advantages and limitations of the proposed methods are in the better understanding of EMR theory that relates emergy and money. In this way, the microeconomic EMR proposition for assessing the equity of trades between the agents, based on what is available in theory, could be understood as the main strength of this method. Thus, the proposed method suggests making the evaluations fairer by showing the reality of exchanges more accurately (like a "magnifying glass" perspective). On the other hand, limitations lie in the fact that both the employed statistical model and the theory of EMR are still in their early stages and need further development and discussion. Therefore, approaches that seek to better understand the EMR are also limiting factors in achieving a better understanding of the method.

Recommendations for future studies include (i) stratifying food consumption based on income levels; (ii) analyzing the Exchange Emergy Ratio (EER) at each stage (link) of the food production supply chain to identify the primary beneficiaries in exchanges, thereby facilitating informed decision-making and the development of more aligned public policies; (iii) taking into account the cultural aspects of food acquisition and consumption, as well as the regional composition of the basic food basket; and (iv) recognizing that the goal of this study was to present emergy as a complement to existing food security assessment models, claiming that future research should incorporate more robust predictive models.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/resources14010007/s1, Figure S1. Aggregated emergy diagram of a citizen with minimal emergy requirements for the welfare of human individuals, including food, environmental resources (considering only the wind and kinetic energy to avoid double-accounting and the earth cycle) (47.17×10^{13} sej/yr). The emergy contribution to solid waste treatment (298.31×10^{13} sej/yr) was considered for the entire household. Work, sleep, and leisure were included as outputs (adapted from Odum, [13]; Brandt-Williams, [68]; Nacimento et al. [53]); Table S1. Emergy exchange ratio (EER) estimative between the consumer (household) and food sup-

ply chain (this study); Table S2. Category, energy composition, and transformity of the food basket by item [14,44,47–51]; Table S3. Estimative of annual food acquisition (this study); Table S4. Estimative of the emergy/money ratio according to the household income (this study); Figure S2. Comparison of the emergy/money ratio according to the household income and Brazilian emergy/money ratio according to Giannetti et al. [69]; Table S5. Estimation of annual food prices (this study).

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