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PRESENTATION

Science is a field of knowledge in which different disciplines intertwine to form a greater whole. **Overview of Agricultural and Biological Sciences: Expanding Knowledge - 2° Ed** is a work that expands this interconnection, bringing together 10 articles on various topics, written by experts from different areas of knowledge.

Developed by **Seven Publications**, this book presents a broad overview of the challenges, discoveries and advances in fields such as refrigerated raw milk, ionizing radiation in agriculture, the mucilage of forage cactus and much more.

SUMMARY

QUALITY PARAMETERS OF REFRIGERATED RAW MILK PRODUCED IN THE NORTHERN REGION OF ESPÍRITO SANTO, BRAZIL

PARÂMETROS DE QUALIDADE DE LEITE CRU REFRIGERADO PRODUZIDO NA REGIÃO NORTE DO ESPÍRITO SANTO, BRASIL

PARÁMETROS DE CALIDAD DE LA LECHE CRUDA REFRIGERADA PRODUCIDA EN LA REGIÓN NORTE DE ESPÍRITO SANTO, BRASIL

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ABSTRACT

The objective of this study was to evaluate the quality parameters of raw milk samples stored in individual refrigeration tanks on three family farms in the northern region of Espírito Santo. Microbiological quality was assessed by analyzing the total bacterial count (TBC) and psychrotrophic bacteria count (PBC). Proximate composition was also determined using a Lactoscan® device, and somatic cell count (SCC) was measured using a Somaticell® kit. Some characteristics of the farms, the location of the tanks, and the temperature used during storage were assessed. Total bacterial count values were within the legally established limit, and the psychrotrophic bacteria count was below the 10% suggested TBC. The average somatic cell count obtained in samples collected from tank A was 650,000 SC/mL, from tank B it was 500,000 SC/mL, and from tank C it was 250,000 SC/mL. Regarding the centesimal composition, it was observed that the milk samples obtained from tanks A and B presented percentages of fat, solids-non-fat, and total solids below the legally recommended values, while the milk samples from tank C presented rates above or close to the established minimum values. In contrast, the percentages of protein and lactose approached the recommended minimum limits. The data showed that the temperature values recorded in the three refrigeration tanks were in accordance with the legislation. Regarding psychrotrophic bacteria, the values were below those suggested in the literature, but it is necessary to reinforce care and surveillance regarding somatic cells, which are indicative of mastitis in the

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herd. Continued frequent evaluation of the parameters analyzed in other samples will be of great importance, as it will contribute to monitoring possible failures in production and processing and will enable the supply of adequate milk and dairy products, in addition to the sustainability of the sector in the northern region of the state of Espírito Santo, Brazil.

Keywords: Family Farming. Psychrotrophic Bacteria. Somatic Cells. Refrigerated Raw Milk. Quality.

RESUMO

Objetivou-se neste trabalho avaliar os parâmetros de qualidade em amostras de leite cru armazenado em tanques de refrigeração individuais localizados em três propriedades rurais familiares situadas na região norte do Espírito Santo. Para avaliação da qualidade microbiológica foram realizadas análises de contagem bacteriana total (CBT) e a contagem de bactérias psicrotróficas (CBP). Realizou-se também a composição centesimal por meio do aparelho Lactoscan® e contagem de células somáticas (CCS) utilizou-se o Kit Somaticell®. Verificou-se algumas características das propriedades rurais, o local de instalação dos tanques e a temperatura empregada durante o armazenamento. Valores da contagem bacteriana total apresentaram-se no limite estabelecido pela legislação e a contagem de bactérias psicrotróficas ficou abaixo de 10% sugeridos em relação a CBT. A contagem média de células somáticas obtida em amostras coletadas no tanque A foi de 650.000 CS/mL, no tanque B foi de 500.000 CS/mL e no tanque C foi de 250.000 CS/mL. Com relação à composição centesimal, observou-se que as amostras de leite obtidas nos tanques A e B apresentaram percentuais de gorduras, sólidos não gordurosos e sólidos totais abaixo do que é recomendado pela legislação, enquanto as amostras de leite do tanque C apresentaram taxas acima ou próximas aos valores mínimos estabelecidos. Em contrapartida, o percentual de proteína e lactose aproximaram-se dos limites mínimos preconizados. Os dados mostraram que valores da temperatura registrada nos três tanques de refrigeração estavam de acordo com a legislação. Com relação às bactérias psicrotróficas, os valores ficaram abaixo dos sugeridos pela literatura, porém é preciso reforçar o cuidado e a vigilância em relação às células somáticas, indicativo de mastite no rebanho. A continuidade da avaliação frequente dos parâmetros analisados em outras amostras será de grande importância pois contribuirá para monitoramento de possíveis falhas na produção e processamento e permitirá o fornecimento de leite e produtos lácteos adequados, além da sustentabilidade do setor na região norte do estado do Espírito Santo, Brasil.

Palavras-chave: Agricultura Familiar. Bactérias Psicrotróficas. Células Somáticas. Leite Cru Refrigerado. Qualidade.

RESUMEN

El objetivo de este estudio fue evaluar los parámetros de calidad de muestras de leche cruda almacenadas en tanques de refrigeración individuales en tres granjas familiares en la región norte de Espírito Santo. La calidad microbiológica se evaluó mediante el análisis del recuento bacteriano total (TBC) y el recuento de bacterias psicrotróficas (PBC). La composición proximal también se determinó utilizando un dispositivo Lactoscan®, y el recuento de células somáticas (RCS) se midió utilizando un kit Somaticell®. Se evaluaron algunas características de las granjas, la ubicación de los tanques y la temperatura utilizada durante el almacenamiento. Los valores del recuento bacteriano total estuvieron dentro del límite legalmente establecido, y el recuento de bacterias psicrotróficas fue inferior al 10% sugerido de TBC. El recuento promedio de células somáticas obtenido en las muestras colectadas del tanque A fue de 650,000 SC/mL, del tanque B fue de 500,000 SC/mL, y del tanque C fue de 250,000 SC/mL. En cuanto a la composición centesimal, se observó que las muestras de leche obtenidas de los tanques A y B presentaron porcentajes de grasa, sólidos no grasos y sólidos totales inferiores a los valores recomendados legalmente, mientras que las muestras de leche del tanque C presentaron valores superiores o cercanos a los valores mínimos establecidos. Por el contrario, los porcentajes de proteína y lactosa se acercaron a los límites mínimos recomendados. Los datos mostraron que los valores de temperatura registrados en los tres tanques de refrigeración se ajustaron a la legislación. En cuanto a las bacterias psicrotróficas, los valores fueron inferiores a los sugeridos en la literatura, pero es necesario reforzar la vigilancia de las células somáticas, que son indicativas de mastitis en el rebaño. La evaluación frecuente y continua de los parámetros analizados en otras muestras será de gran importancia, ya que contribuirá al monitoreo de posibles fallas en la producción y el procesamiento y permitirá el suministro de leche y productos lácteos adecuados, además de la sostenibilidad del sector en la región norte del estado de Espírito Santo, Brasil.

Palabras clave: Agricultura Familiar. Bacterias Psicrotróficas. Células Somáticas. Leche Cruda Refrigerada. Calidad.

1 INTRODUCTION

Milk is a food of fundamental importance for human health. It has many nutrients available and when the hygiene standards recommended in the production process are neglected, it can provide favorable conditions for microbial multiplication by altering its physicochemical characteristics. It is notorious that its microbiological quality is multifactorial and depends, among others, on the state of health of the mammary gland and the outside of the udder, hygiene of the milking equipment, maintenance and correct functioning of the cooling tank, the quality of the water, as well as the adoption of good practices throughout the production chain, aiming to obtain a product with quality and safety for the final consumer (TEIXEIRA et al., 2018; COSTA, 2006). And if after milking the milk is not in adequate storage and refrigeration conditions, there is the possibility of the development and multiplication of undesirable microorganisms, making it unsuitable for consumption (OLIVEIRA, MARCHIORE, 2017).

According to the Regulation of Industrial and Sanitary Inspection of Products of Animal Origin (RIISPOA), milk is the product of complete, uninterrupted milking, in hygienic conditions, of healthy, well-fed and rested cows (BRASIL, 2020). Even with the predominance of small and medium-sized rural properties, the milk and dairy products sector in Brazil is of great economic and social importance, in addition to promoting job creation around 4 million people, both directly and indirectly (ZOCCAL, 2018). However, it is notorious that to this day, due to various economic, structural and cultural factors, not all rural producers are able to fully comply with the legislation.

Studies show that milk production in some regions of the country faces challenges, requiring the adoption of improvements in the management used to obtain and store milk and its derivatives and, otherwise, it can compromise the quality of raw milk and the competitiveness of the sector, in addition to becoming carrier vehicles for undesirable bacteria such as psychrotrophs, among others (RAMOS et al., 2014; NETA et al., 2015; GUTH et al., 2022; MASSINI et al., 2023; STRÖHER et al., 2023, COTTA et al., 2020). In addition, it is necessary to periodically check animal health, especially in relation to mastitis, which is a disease that contributes to changes in the centesimal composition of milk and implies a reduction in the volume produced, generating economic losses for the producer.

For this, there are analyzes that seek to identify the microbial groups present in milk and dairy products, such as mesophilic bacteria, psychrotrophic bacteria, and pathogenic microorganisms, among others. The total mesophile count or total bacterial count (TBC) is an important indicator of milk quality, as high counts indicate the presence of spoilage microorganisms (CASSOLI et al., 2016). TBC is influenced by several factors, such as milking hygiene, storage time and temperature, seasonal factors, such as time of year and climatic conditions, among others (TAFFAREL et al., 2013). However, when good production practices are neglected, refrigeration contributes to the development of psychrotrophic bacteria, which have the capacity to produce thermostable lipolytic and proteolytic enzymes, which maintain their enzymatic activity after pasteurization, or even after the treatment used to obtain UH (ultra-high temperature) milk (BELOTI, 2015; FELIPUS, 2017).

There are several species of psychrotrophic bacteria that can develop in milk at refrigeration temperature, such as *Pseudomonas fluorescens, Pseudomonas putida, Aeromonas hydrophila, Aeromonas sóbera, Aeromonas caviae, Burkholderia cepacia, Klebsiella oxytoca, Ewingella americana, Hafnia alvei, Chryseomonas luteola, Alcaligenes feacalis, Methylobacterium mesophilicum* and *Sphingomonas paucimobilis.* And among these bacteria, the genus *Pseudomonas* spp., stands out for its proteolytic activity associated with the deterioration of dairy products (LAMPUGNANI et al., 2019; ARCURI et al., 2008).

Regarding the proximate composition, milk is formed by lipids, carbohydrates, proteins, mineral salts and vitamins and represent approximately 12 to 13% of milk, and water approximately 87%. Solid elements, their distributions and interactions are determinant for the structure, functional properties and suitability of milk for processing and manufacturing dairy products (DALPIAZ et al., 2018).

Another important analysis in verifying milk quality, both for producers who store milk in individual and collective tanks, is the somatic cell count (SCC), as it is possible to make an assessment of the health of the mammary gland, since this test is an indication of the degree of inflammation. Bovine mastitis is characterized by an infection of the mammary parenchyma that affects a large part of dairy herds, and the highest incidence of cases is of bacterial etiology, but can also occur due to fungal infection (de GOUVEIA et al., 2022). And this disease can present itself in clinical or subclinical forms. The first presents evident signs, such as edema and increased udder temperature, hardening, pain, lumps and pus at the site, and changes in the characteristics of the milk (COSER et al., 2012). The subclinical form, on the other hand, despite not showing visible signs of inflammation in the udder, is characterized by an increase in the number of somatic cells, an increase in chlorine and sodium contents, in addition to a decrease in the levels of casein, lactose and fat, affecting the quality and volume of the milk produced. (COSTA et al. 2017; DEMEU et al. 2016; STRÖHER et al. 2023).

The studies reinforce that mastitis significantly alters the physicochemical parameters of milk, compromising both nutritional and industrial quality. In a study carried out by Liu et al. (2023), the authors highlighted that molecular interventions represent a promising strategy to mitigate the inflammatory impacts associated with subclinical mastitis in cows, contributing to the reduction of antimicrobial use and would involve the use of technologies that would modulate gene expression and cellular processes related to the inflammatory response.

This analysis should be seen as an extremely valuable tool that, among other purposes, allows the monitoring of the prevalence of subclinical mastitis in the herd, especially those caused by contagious microorganisms. In addition to providing important information about the quality of raw milk to the industry, it indicates the hygienic conditions under which the milk was produced on the properties, the possibility of estimating milk production losses, guides the producer to make decisions in order to prevent the transmission of mastitis during lactation, identification of cows for treatment, drying and disposal (LANGONI, 2000; SILVA, 2015; VEIGA, 2016).

The Ministry of Agriculture, Livestock and Supply (MAPA) issued Normative Instruction 76 (IN 76), which establishes technical requirements for the identity and quality of refrigerated raw milk, pasteurized milk and type A pasteurized milk. This standard is part of a set of regulations, including Normative Instruction 77 (IN77), which aim to ensure the quality of milk produced in Brazil and which are currently in force (BRASIL, 2018a and 2018b).

The State of Espírito Santo is located in the southeastern region of Brazil and has an area of 1.46 million hectares of pastures intended mostly for beef and dairy cattle. There are about 1.94 million head of cattle in these pastures (IDAF, 2019), with emphasis on the municipalities of Ecoporanga, Linhares and Nova Venécia, which have the largest herds in the state (24% of the total herd) (INCAPER, 2020; IBGE, 2018a). And dairy farming is an activity of significant relevance in the state and stands out for its expressive volume of production and socioeconomic importance. In 2018, 417 million liters of milk were produced, generating a value of around 495.6 million reais (OTAVIANO et al., 2020; IBGE, 2018b).

Regarding production, seventy-five (75%) in the state is supplied by small properties with daily production of up to 100 liters. This activity is of significant importance because it is present in practically all municipalities and contributes to the economic development of Espírito Santo. In the northern region of the state located above the Doce River, which has higher values both in relation to animal herd and milk production (SANT'ANNA, SESSA, 2021).

Considering these facts and the production characteristics of the northern region of Espírito Santo, it is understood the importance of encouraging milk production that guarantees better yields to small producers and the dairy industry, as well as consumer security in acquiring adequate products and in addition, in this region there is a lack of published data on the quality of raw milk.

In this chapter, the quality parameters of raw milk stored in individual refrigeration tanks located in three family farms located in the northern region of Espírito Santo will be addressed. Analyses of microbiological quality, centesimal composition and somatic cell count were carried out, in addition to checking the conditions of the refrigeration tank site and the temperature used during collection. Obtaining this data will allow producers to direct the adoption of more actions aimed at improving the production and obtaining of adequate milk and dairy products, in addition to promoting the sustainability of the sector in the region.

2 METHODOLOGY

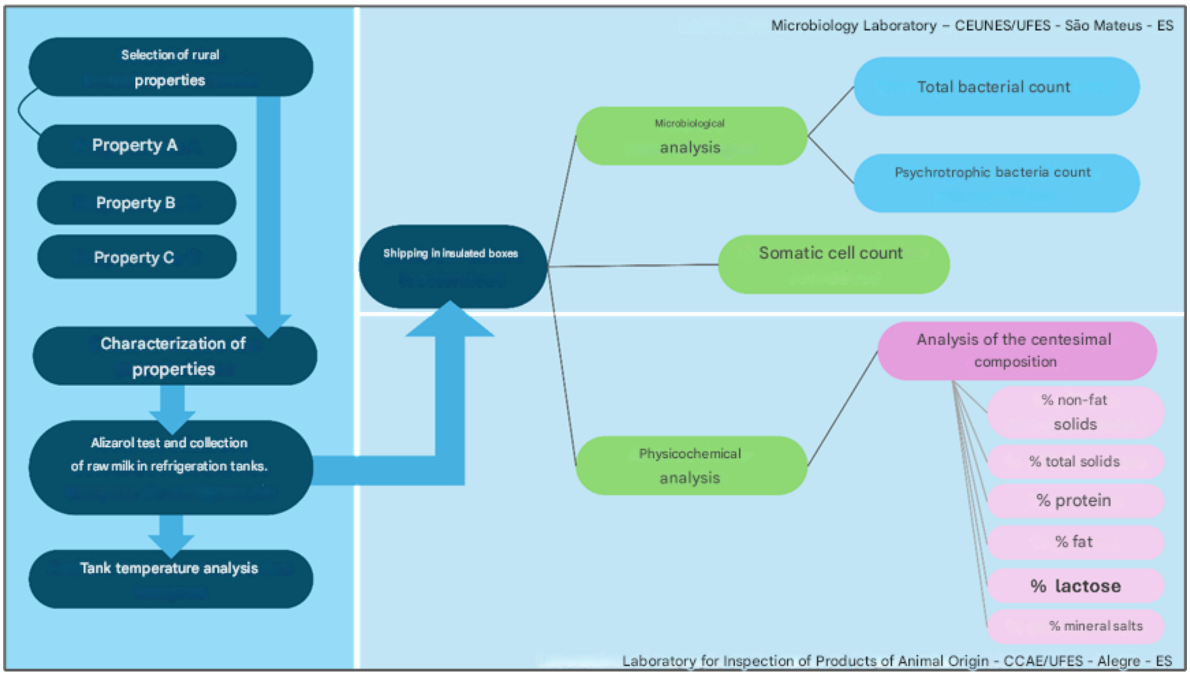
2.1 GENERAL CHARACTERISTICS OF PROPERTIES, INSTALLATION LOCATION AND TEMPERATURE OF TANKS

This research was carried out in a municipality in the northern region of Espírito Santo and three family-based rural properties were inserted and whose producers accepted to participate in the project. The selection of properties was carried out by convenience sampling and in addition, properties that had accessibility difficulties were not included, especially with regard to the infrastructure of side roads and bridges.

Refrigerated raw milk samples were collected and the temperature record values of the individual tanks were recorded. Afterwards, the samples were placed in sterile flasks, using sterile instruments, and then stored in isothermal boxes under refrigeration (between 4 and 8° C). Subsequently, they were transported for microbiological and physicochemical analysis, at the Microbiology Laboratory of UFES – CEUNES in São Mateus - ES and to the Laboratory of Inspection of Products of Animal Origin - LIPOA of the Department of Veterinary Medicine of UFES in Alegre - ES respectively. The order and organization of the project were maintained using the flowchart presented below (Figure 1).

Figure 1

Microbiological, physicochemical analysis and somatic cell count in refrigerated raw milk samples



Source: The authors.

2.2 MICROBIOLOGICAL ANALYSES

Total bacterial count (TBC)

Dilutions of milk samples were performed in sterile saline solution (0.85%) (w/v) and sowing on Standard Count Agar (PCA), using the depth seeding technique. After solidification, the plates were incubated at 35° C/24 h. Plate counting was performed and the results obtained were expressed in CFU/mL according to APHA (2001). The Ministry of Agriculture, Livestock and Supply (MAPA), through Normative Instruction No. 76 of November 2018, establishes a maximum limit of 300,000 CFU/mL of raw milk (BRASIL, 2018a).

Psychrotrophic Bacteria (PBC) Count

To perform the psychrotrophic bacteria count, the same methodology described in the previous item was used, with changes only in temperature and incubation time, which were 7° C/10 days. After the incubation period, the counts were performed and the results were expressed in CFU/mL according to the APHA (2001).

2.3 PHYSICOCHEMICAL ANALYSIS:

Determination of the centesimal composition of milk samples

The analyses of protein, fat, lactose, total solids and mineral salts were carried out at the Laboratory of Inspection of Products of Animal Origin (LIPOA) of the Center for Agrarian Sciences and Engineering of UFES in Alegre - ES. The analysis was performed in an automated manner using the Lactoscan® device. The tests were performed in triplicate and the results found were compared with the legislation (Normative Instruction No. 76, of MAPA) (BRASIL, 2018a).

2.4 DETERMINATION OF SOMATIC CELL COUNT (SCC)

The somatic cell count (SCC) was determined using the Somaticell® Kit. The analyses were carried out following the manufacturer's guidelines. In a specific tube provided by the manufacturer, in the vertical position, 2 mL of reagent was added and then, with the aid of a Pasteur pipette, 2 mL of milk was added. The mixture was homogenized with the aid of a stick, making 30 consecutive vertical movements for 20 to 24 seconds. Afterwards, the tube was sealed and inverted for 20 seconds and returned to its initial position, after 5 seconds the tube was read on a graduated scale. Refrigerated raw milk from individual tanks or for community use must have quarterly geometric means of SCC of a maximum of 500,000 CS/mL (BRASIL, 2018a).

3 RESULTS AND DISCUSSION

3.1 GENERAL CHARACTERISTICS OF THE PROPERTIES, INSTALLATION LOCATION AND TEMPERATURE OF THE TANKS

In this study, periodic collections were carried out in three different family farms with different profiles and were named A, B and C and manual milking was performed and all samples were stable to the alizarol 72º GL test. Property A is located in the rural area and, in terms of herd size and infrastructure, the property is small and easily accessible, in terms of the structural quality of the roads and geographical location. Property B was located in the rural area, is medium-sized and difficult to access, as the structural quality of the roads was relatively compromised. Property C was located in the urban area, medium in size and easily accessible.

In addition, the properties of the present study had individual refrigeration tanks that specifically met the demands of the respective properties. The milk cooling and storage tank, for individual or community use, must be installed on the rural property in an appropriate place, provided with walls, roofing, paving, lighting, ventilation and running water point

(BRASIL, 2018a). And in relation to the hygiene and cleaning of the installation site, no non-conformities were observed and not even at the time of collections, such as insects or the presence of domestic animals. It was found that the average temperature value recorded in tank A was 3.87º C, that of tank B was 4.3º C and that of tank C, 2.4° C and that they were in accordance with the legislation being a determining factor in the quality of the milk, since the inadequate temperature directly influences bacterial growth. The legislation establishes that milk at the refrigeration station must be kept at a maximum temperature of 4º C (BRASIL, 2018a).

In studies carried out on milk production conditions in some family farms located in the municipality of Alegre – ES and in São Mateus – ES, the authors observed several non-conformities related to good production practices not only during milking, but also before and during its storage in refrigeration tanks, requiring adjustments in milk production management (JUNQUEIRA et al., 2015; RAMOS et al., 2014; LACERDA, 2014; NETA et al., 2016; NETA et al., 2018; PICCOLO et al., 2018; ULISSES et al., 2022; MASSINI et al., 2023).

3.2 TOTAL BACTERIAL COUNT (CBT) AND PSYCHROTROPHIC BACTERIA COUNT (CBP)

The mean values of total bacterial count (TBC) and psychrotrophic bacteria count (PBC) are shown in Table 1.

Table 1

Mean values of total bacterial count (TBC) and psychrotrophic bacteria count (PBC) in refrigerated raw milk samples.

Cooling tank (individual)	CBT (CFU/mL)	CBP (CFU/mL)	% BP/BT
A	7.24×10^4	4.98×10^2	0,68%
B	2.57×10^4	NR	-
C	6.60×10^4	NR	-

NR: Non-representative (count less than 25 CFU/mL); CBT: Total Bacterial Count; CBP: Psychotrophic Bacteria Count. % BP/BT: Percentage of psychrotrophic bacteria/total bacteria.

In this study, regarding the total bacterial count (TBC), no sample presented values above what is recommended by IN 76/2018, which establishes that refrigerated raw milk from individual tanks or for community use must have quarterly geometric averages of a maximum of 300,000 CFU/mL. And the psychrotrophic bacteria (PBC) count was less than 10% of the TBC. One hypothesis for this low count may be related to the shorter time the milk was stored in the refrigeration tanks and because they are individual. In Brazil, there are no values for psychrotrophic bacteria in the legislation, however, these results are in accordance with what was suggested by Cousin (1982). According to the author, values higher than 10% of mesophilic values should not be recommended considering that many species belonging to this group of microorganisms have high spoilage potential, and thus can compromise the harmlessness of the product mainly due to the proteolytic capacity of these microorganisms.

In addition, it was also observed the conformity in relation to the effect of maintaining the adequate temperature and storage time of milk in cooling tanks on dairy farms with microbial growth being a parameter of importance for the maintenance of the microbiological and physicochemical quality of raw milk. In other words, maintaining the appropriate temperature contributed both to the quality of the milk and to the reduction of economic losses, generating sustainability for the sector. It is important to emphasize that cooling milk after obtaining it is the widely accepted method to minimize the speed of multiplication of mesophilic microorganisms, which are usually responsible for the deterioration of this product.

Massini et al., (2023), obtained high values for the count of psychrotrophic bacteria in raw milk collected in a municipality in the southern region of Espírito Santo. In one of the samples that was obtained in a collective tank, it presented values of 107 CFU/mL. These values could be attributed to the mixture of milk from several properties in a single tank, which favors contamination and subsequent bacterial multiplication.

Neta et al., (2016), when analyzing the quality of raw milk stored in four refrigeration tanks in the southern region of ES, concluded that high values of mesophilic and psychrotrophic bacteria found were indicative of failures in the procedures used in hygiene and due to inappropriate production and storage conditions. In addition, all refrigeration tanks were of the collective type and in this case, there were greater possibilities of contamination considering the mixture of milk from several rural properties.

Some genera of psychrotrophic bacteria produce thermostable extracellular enzymes, mainly proteases and lipases, which degrade milk components and, consequently, alter the characteristics of dairy products. Goulart et al. (2021), evaluated the physicochemical characteristics of natural yogurts produced from milk contaminated by proteolytic psychrotrophic bacteria. The presence of proteases can alter the composition of yogurt, degrading the proteins into smaller water-soluble peptides that are lost in whey separation. The authors observed that the longer the time spent in refrigeration, without appropriate heat treatment, favored the multiplication of these bacteria and found that good production practices should not be neglected, which are related to lower CBT values and, consequently, lower values of psychrotrophic bacteria.

According to Ströher et al. (2023), when analyzing refrigerated raw milk quality parameters from 33 (thirty-three) small dairy farms in Vale do Taquari, RS, the authors concluded that three milk producers showed non-conformities in the analysis of Standard Plate Count or TBC of refrigerated raw milk (8.57%), with values of 11,000 CFU/mL as the overall average. This is an analysis that classifies the microbiological quality of milk, as it measures the aerobic mesophilic bacteria present in it.

Alves (2024), evaluated the microbiological quality of raw milk samples obtained from 155 rural properties located in the interior region of the state of Goiás, through the analysis of total bacterial count, psychrotrophic bacteria and somatic cells. The author reported that for the values obtained for total bacterial count, they were mostly low, ranging from 2,000 to 125,000 CFU/ml, suggesting good hygiene and milking practices and positive results for psychrotrophic bacteria with CFU/mL counts ranging from 10^1 to 10^3.

Santana et al. (2021), evaluated the quality of refrigerated raw milk collected in 12 different tanks, which were collective and individual located on rural properties in the municipality of Ouro Preto do Oeste -RO and found lower CBT values ranging from 8.9 x105 and 7.1x105 CFU/mL in samples collected in tanks with lower temperature values around 4.9° C and 6.1° C, respectively, while in another tank that presented a temperature of 14.7° C at the time of collection, the values were CBT 2.2 x 106 CFU/mL.

Psychrotrophic bacteria have high deteriorating potential, and thus can compromise the harmlessness of the product, mainly due to the proteolytic capacity of these microorganisms. Another risk factor inherent to the presence of these microorganisms in milk is the formation of biofilm by bacteria of the genus *Pseudomonas* spp. (MANN; WOZNIAK, 2012), which are bacterial communities surrounded by a polysaccharide matrix, conferring high resistance and persistence to contamination control methods (SOUZA et al., 2021).

When evaluating samples of cheese from raw milk in the northwest region of São Paulo, researchers identified the presence of pathogenic agents, including *Listeria* spp., detected in 68 (64.14%) of the 106 samples obtained from bovine feces, swabs from the hands of milkers and cheesemakers, buckets, raw milk, whey, water, surfaces and utensils of cheese production (RIBEIRO et al., 2022). And in this same study, the authors evaluated 391 isolates of *Staphylococcus* spp., which were obtained from samples of raw milk, milkers' hands, whey, utensils, and cheeses. Of this amount, 60 (15.31%) were identified as *Staphylococcus aureus* by PCR (*Polymerase Chain Reaction*), and of these, 15.31% had virulence genes (*eta, hlg, seg, seh, sei*).

Ribeiro Júnior et al., (2018) in order to identify, quantify and evaluate the deteriorating activity of *Pseudomonas* spp. in bovine milk produced in the state of Paraná, obtained plate counts of *Pseudomonas* spp. that ranged from <10 to 1.3 x 103 CFU/mL, with an average of 0.89 (±3) x 102 CFU/mL. The detection of this psychrotrophic bacterium in milk is a risk for producers and consumers, due to its ability to interfere with the shelf life and sensory characteristics of this product, in addition to being an important pathogenic agent.

3.3 COMPOSITIONAL EVALUATION OF MILK SAMPLES

The results of the centesimal composition analysis are shown in Table 2.

Table 2

Centesimal composition of raw milk samples stored in individual refrigeration tanks

Parameters	**A**	**B**	**C**	**Legislation IN 76/2018[1] Recommended minimum**
Fat (%)	2,47 %*	2,86 %*	3,67 %	3,0 %
Non-greasy solids (%)	7,97 %*	8,05 %*	8,00 %*	8,4 %
Total Solids (%)	10,44 %*	10,92 %*	11,68 %	11,4 %
Protein (%)	2,87 %*	2,95 %	2,92 %	2,9 %
Lactose (%)	4,38 %	4,43 %	4,40 %	4,3 %
Mineral salts (%)	0,64 %	0,65 %	0,65 %	_

[1]Normative instruction 76 (BRASIL, 2018a). * values lower than the standard established by IN 76/2018.

In this work, in relation to the centesimal composition, it was observed that the milk samples obtained in the tanks of properties A and B presented percentages of fats, non-fat solids and total solids below what is recommended by IN 76/2018, while the milk samples of tank C presented rates above or close to the values established by the current legislation.

On the other hand, the protein and lactose values were closer to the recommended minimum limits. These values can be influenced by several factors, such as season, health, breed and, especially, the animal's diet (FRIGERI et al., 2020; PACHECO, 2011). Neiva Júnior et al.,2021, when analyzing the centesimal composition of bovine milk samples, observed the following results: fat 3.5%; protein: 3.1%; lactose: 4.5%; total solids: 12.04% and non-fat solids 8.5%, without observing changes in composition between the dry and rainy seasons, all within the desirable standard.

The substantial reduction of the lactose concentration or total solids in the milk suggests fraudulent addition of water after milking, which affects the quality and authenticity of the product. On the other hand, variations in the concentration of proteins, fats, and lactose can directly impact the physical and functional properties of milk, affecting its processing, stability, and the quality of dairy products (BRITO et al., 2021).

3.4SOMATIC CELL COUNT (SCC)

In this study, the mean somatic cell counts were 650,000 CS/mL in milk samples stored in tank A, 240,000 CS/mL in tank B, and 500,000 CS/mL for tank C. Thus, only the milk samples obtained in tank A presented higher counts in disagreement with the current legislation, and it was the same sample that presented the most alterations in the centesimal composition, for several parameters analyzed. High somatic cell counts are directly related to the centesimal composition of milk, with a decrease in noble groups of nutrients such as fat and protein (MONTANHINI et al., 2013). Cell count is a parameter related to herd health and directly interferes with centesimal composition.

The main etiologic agents of mastitis are *Staphylococcus aureus*, *Streptococcus agalactiae*, *Corinebacterium* sp. *Mycoplasma bovis*, although mycoplasmas, yeasts and algae of the genus *Prototheca* are also reported (BARKEMA et al., 2009; ZADOKS et al., 2011). Mastitis represents a serious concern within the milk production chain due to the great losses it causes and not only changes in quality and impact on the reduction of the volume of milk produced (MASSINI et al., 2023; SANTOS et al., 2022; PICCOLO et al., 2018). In addition, it is a disease and should not be neglected and can be clinical, when the externalization of symptoms occurs, and subclinical, when the externalization of symptoms does not occur. The value obtained from somatic cells may be indicative of subclinical mastitis, a very frequent situation in herds and which requires monitoring (MASSOTE et al., 2019). On the other hand, the average value of somatic cells obtained in samples from tank C indicates a count within the limit established by legislation. This means that greater care must be taken with the hygiene of the teats, as proper hygiene of the mammary gland may be the most important single measure in the prevention of new intramammary infections (LIMA et al., 2022). The main form of prophylaxis for this clinical condition is to follow good manufacturing practices, such as the adoption of "milking line" practices, adequate pre- and *post-dipping*, personal hygiene care of milkers, keeping animals standing after milking, among others (MASSOTE et al., 2019).

In a study carried out by Alves (2024), the author evaluated the microbiological quality of raw milk samples obtained from 155 rural properties located in the interior region of Goiás, through somatic cell count (SCC) analyses. It was found that 81.81% of the samples analyzed had high counts and outside the standard established by the legislation, most of them exceeding 500,000 CS/ml, which indicated health problems in the herd.

Thus, it is imminent to continue the work with the participation of other rural producers to monitor the quality of refrigerated raw milk in the northern region of ES.

4 CONCLUSION

With these facts presented, it was concluded that the milk samples were in accordance with the current legislation, with regard to the total bacterial count. And the adequate storage temperature verified in the refrigeration tanks played a crucial role in preserving the quality of the milk, however, somatic cell values above those established by the legislation indicated the presence of mastitis, in addition to directly impacting the centesimal composition of the milk and influencing the process of action of the lactic cultures used in the preparation of dairy products.

It is of fundamental importance to adopt good agricultural practices, including verification of animal health and diet, as such procedures are indispensable to ensure the quality and supply of milk and dairy products to the consumer. By implementing and adopting rigor in relation to hygiene and sanitization at all stages of the production chain, producers can mitigate risks related to public health and raise the quality of milk for the consumer. The continuation of research is imminent and all this will contribute to the sustainability of the milk and dairy products sector in the northern region of Espírito Santo and to the health of the population.

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FOOD PACKAGING: MATERIALS, PROPERTIES, MANUFACTURING AND CHALLENGES FOR SUSTAINABILITY IN MOZAMBIQUE

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ABSTRACT

Packaging is a strategic element in the food value chain, going beyond simple packaging to include protection, preservation, transportation, communication, and marketing. This chapter reviews the main packaging materials—metal, plastic, glass, cellulose, and wood—highlighting their properties, manufacturing processes, applications, and limitations. It also addresses the issue of compound migration, food safety risks, quality control methods, and the importance of recycling and sustainability in the sector. Globally, there is a drive for smart, biodegradable packaging and returnable systems aligned with the circular economy. However, in Mozambique, one of the biggest challenges remains limited access to adequate packaging, both due to dependence on imports and the lack of local processing industries. As a result, much of the post-harvest agricultural and horticultural produce is sold or stored unprotected, often exposed to the elements, which increases losses, reduces quality, and compromises food safety. The Mozambican legal framework, defined by Decree No. 15/2006, Ministerial Order No. 247/2011, and the recent Order No. 26/2025, establishes standards for labeling, safety, and sustainability. However, structural limitations persist in inspection and laboratory control, especially in migration and certification testing. Cases such as the use of returnable bottles by Cervejas de Moçambique and the ISO 22000 certification of Água da Namaacha demonstrate significant progress, but are still limited to large companies. Therefore, strengthening the packaging industry in Mozambique, combined with public incentive policies, training programs, and investment in quality laboratories, is essential to reduce post-harvest losses, add value to products, and promote the country's competitiveness in domestic and international markets.

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Keywords: Packaging. Food Safety. Post-harvest. Sustainability. Mozambique.

RESUMO
A embalagem constitui um elemento estratégico na cadeia de valor dos alimentos, indo além da simples função de acondicionamento para atuar na proteção, conservação, transporte, comunicação e marketing. Este capítulo revisa os principais materiais de embalagens metálicas, plásticas, de vidro, celulósicas e de madeira destacando suas propriedades, processos de fabricação, aplicações e limitações. Aborda-se ainda a problemática da migração de compostos, os riscos para a segurança alimentar, os métodos de controle de qualidade e a importância da reciclagem e sustentabilidade no setor. No contexto global, observa-se a busca por embalagens inteligentes, biodegradáveis e sistemas de retornabilidade, alinhados à economia circular. Contudo, em Moçambique, um dos maiores desafios continua sendo o acesso limitado a embalagens adequadas, tanto pela dependência de importações como pela carência de indústrias locais de transformação. Como consequência, grande parte da produção agrícola e hortícola pós-colheita é comercializada ou armazenada sem proteção, frequentemente exposta ao relento, o que aumenta perdas, reduz a qualidade e compromete a segurança alimentar. O enquadramento legal moçambicano, definido pelo Decreto n.º 15/2006, pelo Diploma Ministerial n.º 247/2011 e pelo recente Diploma n.º 26/2025, estabelece normas de rotulagem, segurança e sustentabilidade. Contudo, persistem limitações estruturais na fiscalização e no controlo laboratorial, especialmente em ensaios de migração e certificação. Casos como a utilização de garrafas retornáveis pela Cervejas de Moçambique e a certificação ISO 22000 da Água da Namaacha mostram avanços importantes, mas ainda restritos a grandes empresas. Assim, o fortalecimento da indústria de embalagens em Moçambique, aliado a políticas públicas de incentivo, programas de capacitação e investimento em laboratórios de qualidade, é essencial para reduzir perdas pós-colheita, agregar valor aos produtos e promover a competitividade do país nos mercados interno e externo.

Palavras-chave: Embalagens. Segurança Alimentar. Pós-colheita. Sustentabilidade. Moçambique.

RESUMEN
El embalaje es un elemento estratégico en la cadena de valor alimentaria, yendo más allá del simple embalaje para incluir protección, conservación, transporte, comunicación y marketing. Este capítulo revisa los principales materiales de embalaje (metal, plástico, vidrio, celulosa y madera), destacando sus propiedades, procesos de fabricación, aplicaciones y limitaciones. También aborda el problema de la migración de compuestos, los riesgos de inocuidad alimentaria, los métodos de control de calidad y la importancia del reciclaje y la sostenibilidad en el sector. A nivel mundial, existe un impulso para envases inteligentes, biodegradables y sistemas retornables alineados con la economía circular. Sin embargo, en Mozambique, uno de los mayores desafíos sigue siendo el acceso limitado a envases adecuados, tanto por la dependencia de las importaciones como por la falta de industrias de procesamiento locales. Como resultado, gran parte de los productos agrícolas y hortícolas poscosecha se venden o almacenan sin protección, a menudo expuestos a los elementos, lo que aumenta las pérdidas, reduce la calidad y compromete la inocuidad alimentaria. El marco legal mozambiqueño, definido por el Decreto n.º 15/2006, la Orden Ministerial n.º 247/2011 y la reciente Orden n.º 26/2025, establece normas de etiquetado, seguridad y sostenibilidad. Sin embargo, persisten limitaciones estructurales en la inspección y el control de laboratorio, especialmente en las pruebas de migración y certificación. Casos como el

uso de botellas retornables por parte de Cervejas de Moçambique y la certificación ISO 22000 de Água da Namaacha demuestran avances significativos, pero aún se limitan a las grandes empresas. Por lo tanto, el fortalecimiento de la industria del envasado en Mozambique, junto con políticas públicas de incentivos, programas de capacitación e inversión en laboratorios de calidad, es esencial para reducir las pérdidas poscosecha, agregar valor a los productos y promover la competitividad del país en los mercados nacionales e internacionales.

Palabras clave: Envasado. Seguridad Alimentaria. Poscosecha. Sostenibilidad. Mozambique.

1 INTRODUCTION

Packaging is one of the most strategic elements in the food production and consumption chain. Its function goes beyond simple packaging: it involves protection against physical, chemical and biological agents; the conservation of sensory and nutritional quality; the facilitation of transport and storage; and communication with the consumer, either through mandatory labeling or marketing strategies.

Historically, the evolution of packaging has followed technological development and changes in consumption habits. From glass and metal to synthetic polymers and cellulosic materials, the diversity of solutions reflects not only industrial advances, but also the growing concern for food safety, sustainability and logistical efficiency.

However, the use of packaging presents global challenges: the migration of toxic compounds, the dependence on non-renewable raw materials, the environmental impact caused by the improper disposal of plastics, and the need to strengthen recycling and returnability systems. In response, innovation trends such as smart, biodegradable and biopolymer-based packaging are emerging, aligned with the principles of the circular economy.

In the Mozambican context, issues related to packaging take on even more critical contours. One of the country's biggest challenges is limited access to adequate packaging, which is reflected in high post-harvest losses, especially in fruits, vegetables and other perishable products, which are often sold or stored outdoors (figure 01). This shortage is the result of dependence on imports, high costs and reduced local capacity for the production of packaging materials. While large companies, such as Cervejas de Moçambique and Água da Namaacha, already adopt modern systems of returnability and quality certification, most small producers and traders lack affordable and sustainable alternatives.

Figure 1

Sale of food products in the wholesale market of Waresta

Source: Authors, 2025.

In addition, Mozambique has important legal instruments, such as Decree No. 15/2006, Ministerial Diploma No. 247/2011 and the most recent Diploma No. 26/2025, which introduces the Environmental Tax on packaging. However, the effective implementation of these standards still faces limitations in inspection, specialized laboratories and the inclusion of small and medium-sized companies in the certification processes.

Given this scenario, studying packaging materials, their functions, properties, risks, and trends is essential not only to understand the global reality, but also to propose solutions adapted to the Mozambican context. This knowledge can subsidize public policies, technological innovation, and business strategies that contribute to reducing losses, adding value, and promoting the sustainability of the food chain in the country.

2 PACKAGING CONCEPTS

Packaging is technically defined as wrappers or containers intended to hold, preserve, and protect food during transportation, storage, and consumption. Its main function is to preserve the integrity and quality of the product until the moment it reaches the final consumer. From an economic point of view, packaging must "protect what it sells and sell what it protects", reinforcing both its function as a barrier against external agents and its role in marketing and commercial differentiation.

The classification of packaging can occur according to different criteria. As for use, there are primary ones, which come into direct contact with food, such as cans, bottles and plastic bags; secondary packaging, which groups primary packaging, such as cardboard boxes and cartridges; and tertiary ones, intended for transport and logistics, such as pallets and containers. As for stiffness, they can be rigid, semi-rigid or flexible. In relation to the material, metallic, plastic, glass, cellulosic and wood stand out. In Mozambique, many products in informal trade use improvised or reused primary packaging, while formal firms tend to employ more standardized solutions; this reality is partially documented in plastic waste studies that show high volumes of mismanaged materials. For example, estimates from the Life Cycle Assessment of Plastic Waste Management in Mozambique study indicate that in 2020, around 480,000 tons of plastic waste are generated in the country, with more than 70% remaining without formal collection. https://link.springer.com/article/10.1007/s10163-024-02098-z?utm_source=chatgpt.com

3 FUNCTIONS OF FOOD PACKAGING

The functions of packaging include containment, protection, conservation, transport and promotion. Containment ensures that the product is properly maintained, preventing loss or dispersion; the protection protects against shocks, light, oxygen, humidity and microorganisms; conservation extends shelf life by maintaining physical, nutritious and sensory properties; transportation and storage facilitate logistics; Finally, promotion and consumer information through labeling, marketing or design play an essential role. In the Mozambican context, protection is of critical importance, as many perishable products, such as fruits and vegetables, are left out in the open or sold without proper packaging, accelerating post-harvest losses, poor quality and reduced market value. Although there are no specific published statistics to date for post-harvest losses associated with the lack of modern metal/plastic/glass packaging, estimates of plastic waste (≈ 116,000 tons discarded per year without proper treatment in 2025) highlight the structural problem of disposal and environmental management that is also reflected in quality losses of perishable foods. https://clubofmozambique.com/news/mozambique-discards-annually-116000-tonnes-of-plastic-284183/?utm_source=chatgpt.com

4 FOOD PACKAGING MATERIALS

Metal packaging, manufactured from aluminum, a very light non-ferrous material, easy to transform and with good resistance to atmospheric oxidation and steel (-FF tinplate, chrome sheet, Stancron sheet and uncoated sheet), stand out for their high mechanical resistance and efficient barrier against oxygen and light, being widely used in preserves, energy drinks and soft drinks.

Metal packaging is widely used in the food industry due to its physicochemical and mechanical properties. Among them, aluminum (Figure 02B) and steel (Figure 02A) stand out, which have distinct characteristics and complementary applications. Aluminum is a low-density non-ferrous metal, easily formable and with high resistance to atmospheric oxidation, and is widely used in the manufacture of packaging. On the other hand, steel sheets (FF tinplates, chrome plates, Stancron sheets and uncoated sheets), consisting essentially of iron and carbon, are characterized by high mechanical strength and durability, and are used in the production of food packaging with various structures. Although steel has a higher susceptibility to corrosion when compared to aluminum, its robustness and relatively low cost justify its wide use in structural applications.

Metal packaging for food is broadly classified into two main types: three-piece packages (Figure 02A) and two-piece packages (Figure 02B). The former consist of a body, lid and bottom, and are commonly manufactured in tinplate. Two-piece packages, on the other hand, have the body and bottom integrated into a single structure, requiring only the application of a lid. This type of packaging can be produced in tinplate, chrome foil or aluminum foil, materials that are distinguished by their composition, resistance to corrosion and suitability for the type of food packaged.

The main metallic materials used in the manufacture of food packaging are tinplate, chrome foil, and aluminum foil, each with specific properties and applications (Zhou et al., 2020).

Tinplate has very good corrosion resistance, good sulfuration resistance, good weldability, and good formability, and is widely used in the production of two- and three-piece cans, as well as metal caps. Its cost is considered average, which makes it a balanced option between performance and economic viability (Zhou et al., 2020). Chrome plate, on the other hand, also has very good corrosion resistance and excellent sulfuration resistance, although it has poor weldability. It stands out for its good forming capacity and low cost, being used mainly in the manufacture of two-piece cans and lids (Kumar et al., 2023). Aluminum foil, on the other hand, offers very good formability and good resistance to sulfuration, but has low corrosion resistance when compared to other materials. Despite this, it is widely used in two-piece cans, easy-open lids, and tubes, due to its lightness, excellent barrier against light, gases, and moisture, as well as being recyclable and safe for food contact (Okorie et al., 2023; Taroco et al., 2024). The choice of material therefore depends on the desired properties in the final product, the type of food to be packaged, and the balance between mechanical strength, cost, and corrosion protection (Zhou et al., 2020; Okorie et al., 2023).

However, they are susceptible to corrosion, which requires the use of internal coatings. In Mozambique, the production of canned fish, such as tuna and sardines, uses this type of packaging, although the metal raw material is largely imported.

Figure 2

Steel (A) and Aluminum (B) metal packaging

The

B

Source:https://id.pngtree.com/freepng/empty-tin-can-tinned_13115417.html; https://mundolatas.com/pt-br/embalagem-dois-pecas-dwi/

Plastic packaging, in turn, is the most versatile and economically accessible, being produced from polymers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC) and polystyrene (PS). They are lightweight, transparent and moldable in different shapes, which makes them widely used in cereal bags, soft drink bottles and snack packaging. However, they have a strong environmental impact due to the low degradation rate and the risk of additive migration.

Plastic packaging can be produced by different industrial processes, including extrusion, thermoforming, injection, and blow molding, as well as injection-blow molding and co-extrusion combinations (Silva et al., 2021; Zhang et al., 2022). In the extrusion process, plastic resin is melted and molded into films, sheets, or tubes, and can be combined with other polymers to form multilayer structures with better barrier properties (Martins & Oliveira, 2020). Thermoforming uses previously extruded sheets, heated to the point of softening and molded by vacuum and pressure, and is common in the production of cups, jars, and trays (García et al., 2023). Injection molding is widely used in the manufacture of high-precision parts, such as caps and containers, due to its ease of automation and low operating cost (Ramos et al., 2022). Blow molding and injection-blow molding are mainly used in the production of bottles, where compressed air conforms the molten plastic in the mold, ensuring good dimensional accuracy and finish (López & Navarro, 2021). In many applications, different materials are combined by co-extrusion, lamination, or coating (metallization), associating polymers, aluminum, and paper to improve the strength, protection, weldability, and printing properties of the packaging (Fernandes et al., 2024; Zhou et al., 2020). In Mozambique, the indiscriminate use of disposable plastic bags in informal commerce has led the government to adopt legal restrictions to mitigate environmental impacts, Coca-Cola Beverages Africa (CCBA) through its PET program has increased the daily amount collected for recycling by about 10 tons/day, creating jobs for hundreds of people. https://www.ccbagroup.com/investment-in-recycling-increases-collection-by-10-tons-a-day/?utm_source=chatgpt.com

The glass packaging, composed of sand, barrel, limestone and recycled shards, offers a total barrier against gases and is fully recyclable and reusable. Its manufacture begins with the inspection of raw materials, evaluating granulometry, density and moisture, ensuring the reproducibility of the process. After approval, the materials are stored in silos, dosed and mixed with precision, including the addition of water and recycled shards. The mixture is then melted in crucible or tank furnaces, reaching temperatures of 1400–1550 °C to obtain a malleable vitreous bath. Then, the mass undergoes refining and conditioning to eliminate gases and homogenize the viscosity. Molding occurs by the blow-blow or pressure-blow process, determining the final shape of the bottles or jars. After forming, the containers are treated on the surface by heat, applying metallic coatings to increase resistance to internal pressure and mechanical shocks. Subsequently, annealing reduces internal stresses, ensuring dimensional stability and thermal resistance. Finally, cold surface treatment is applied, usually with emulsions or fatty acids, to reduce friction, facilitate transport and handling without compromising labeling. Despite their fragility and weight, they remain widely used in beers, soft drinks, wines and olive oils. Cervejas de Moçambique is a success story in the adoption of returnable bottle systems, reducing dependence on imports and production costs.

Cellulosic packaging, produced from paper, paperboard and corrugated cardboard, stands out for its low cost, ease of printing and recyclability, although it has low resistance to moisture. Paper production involves several stages, highlighting the disaggregation of the fibers, the preparation of the pulp, the formation of the sheet, the finishing and the transformation into final products. Disaggregation can occur by mechanical, chemical or semi-chemical methods. In the mechanical method, the wood is crushed and mixed with water, resulting in high yield (90–95%), but with damaged fibers, suitable for low-strength papers such as newspapers. The chemical method selectively removes lignin and carbohydrates, producing high-purity pulp, used in packaging papers and bags. The semi-chemical process, on the other hand, combines mechanical and chemical treatments, generating intermediate resistance pulps, applicable to cardboard kernels. Paste preparation includes defibering, adding additives, bleaching, and mechanical refinement to adjust strength and physical properties. Paper formation occurs in Fourdrinier machines or cylinders, where the pulp is deposited, drained and partially dried, allowing homogeneous or multilayer sheets to be obtained, depending on the type of product. Then, pressing and drying are carried out in heated cylinders, followed by surface treatments that may include calendering, coatings with polyethylene, paraffins, or pigments to provide brightness, smoothness, and barrier properties. The transformation of paper and cardboard involves printing, laminating, corrugating, cutting and creasing, giving specific characteristics for different applications. Corrugated cardboard is formed by gluing the corrugated core to external covers, adjusting the pressure so as not to damage the structure of the waves, ensuring resistance and uniformity. The final products include heat-sealable or glued bags, simple boxes, displays, multipacks and liquid packaging with laminated plastic and aluminum structures, as well as blister packs and composite cans.

In the country, they are widely used to package fruits destined for export, such as mangoes and bananas, although improvised solutions still predominate in the domestic market.

Finally, wooden packaging, traditionally used in the packaging of fruits and vegetables, offers robustness and the possibility of reuse, but presents risks of contamination by pests and high weight. In Mozambique, they continue to be used in local markets, but have been progressively replaced by cardboard or rigid plastic alternatives.

5 COMPONENT MIGRATION AND FOOD SAFETY

Food safety is directly related to the migration of components from packaging to food. Compounds such as heavy metals (lead, cadmium, mercury), plasticizers, bisphenol A, phthalates, and paints can migrate, depending on the composition of the packaging, the food, and the storage conditions.

To monitor this risk, global and specific migration assays are performed with food simulants, such as water, 3% acetic acid solution, 15% alcohol solution, and refined olive oil or n-heptane (tables 1 and 2). The determination of heavy metals is generally done by atomic absorption spectrometry (INSTITUTO ADOLFO LUTZ, 2008).

Table 1

Conditions for testing

CONDIÇÕES DE CONTACTO NO USO REAL	CONDIÇÕES DE ENSAIO				
	Simulante A	Simulante B	Simulante C	Simulante D	
	Água	Ácido acético a 3%	Álcool a 15%	Heptano **	Azeite de oliva *
A. Conservação (contacto prolongado, t > 24 h)					
T < 5°C	5°C/10 dias	5°C/10 dias	5°C/10 dias	5°C/30 min	5°C/10 dias
5°C < T < 40°C	40°C/10 dias	40°C/10 dias	40°C/10 dias	20°C/30 min	40°C/10 dias
B. Contacto breve (2 h < t < 24 h)					
À temperatura ambiente	40°C/24 h	40°C/24 h	40°C/24 h	20°C/15 min	40°C/24 h
C. Contacto momentâneo (t < 2 h)					
À temperatura ambiente	40°C/2 h	40°C/2 h	40°C/2 h	20°C/15 min	40°C/2 h
D. Elaboração					
40°C < T < 80°C	80°C/2 h	80°C/2 h	80°C/2 h	40°C/15 min	80°C/2 h
80°C < T < 100°C	100°C/30 min	100°C/30 min	-	50°C/15 min	100°C/30 min
T > 100°C	120°C/30 min	120°C/30 min	-	60°C/15 min	120°C/30 min

Source: Brazil, 1999.

Table 2

Conditions for migration trials

CONDIÇÕES DE CONTACTO NO USO REAL	CONDIÇÕES DE ENSAIO			
	Simulante A Água	Simulante B Ácido acético a 3% (m/v)	Simulante C Álcool a 15% (v/v)	Simulante D Heptano **
A. Contacto prolongado, t > 24 h				
T < 5°C	20°C/48 h	20°C/48 h	20°C/48 h	20°C/30 min
5°C < T < 40°C	50°C/24 h	50°C/24 h	50°C/24 h	20°C/30 min
B. Contacto breve (2 h < t < 24 h)				
À temperatura ambiente	40°C/24 h	40°C/24 h	40°C/24 h	20°C/15 min
C. Contacto momentâneo (t < 2 h)				
À temperatura ambiente	40°C/2 h	40°C/2 h	40°C/2 h	20°C/15 min
D. Elaboração				
40°C < T < 80°C	65°C/2 h	65°C/2 h	65°C/2 h	40°C/30 min
80°C < T < 100°C	100°C/30 min	100°C/30 min	-	50°C/30 min
T > 100°C	120°C/30 min	120°C/30 min	-	65°C/ 2 h
E. Envasado a quente				
T>70°C	À T de ebulição e esfriar a 38°C	À T de ebulição esfriar a 38°C	-	50°C/15 min

**In the case of paraffin-coated cellulosic material, the total migration test with the n-heptane simulant is not required
Source: Brazil, 1999.

However, in Mozambique, the application of these tests faces significant obstacles. The lack of ISO 17025 accredited laboratories limits the systematic performance of migration analyses, restricting them to large companies that use international laboratories or specialized services such as those of SGS Mozambique. Small and medium-sized producers rarely have access to these tools, which increases food security risks. So far, no recent data (2020-2025) specific migration in Mozambican foods have been published for each type of packaging (metal, plastic, etc.), which highlights a critical research gap.

6 PACKAGING RECYCLING

Recycling is an essential component of sustainable packaging management. Glass can be recycled infinitely while maintaining its original properties, which makes it a highly advantageous material. Metals, such as aluminum and steel, are also recyclable, although they rely on efficient collection systems and reverse logistics. Plastics, on the other hand, still have low overall recycling rates, and in Mozambique the situation is more critical, as there are no structured selective collection systems. Cellulosic materials can be reused, but suffer quality degradation after successive recycling cycles.

When it comes to recycling, Mozambique faces one of the biggest challenges in the improper disposal of plastics, with an estimated 116,000 tons of plastic discarded annually without proper treatment by 2025; only about 1% of these materials are recycled. https://clubofmozambique.com/news/mozambique-discards-annually-116000-tonnes-of-plastic-284183/ Reverse logistics projects are beginning to emerge, such as the CCBA, which subsidizes PET collectors and values returnable plastics, promoting jobs and local income. https://www.ccbagroup.com/investment-in-recycling-increases-collection-by-10-tons-a-day/?utm_source=chatgpt.com. CDM with returnable glass bottles also illustrates this trend; however, the infrastructure for recycling and repurposing remains insufficient to cover the entire country.

In Mozambique, recycling occurs predominantly informally, with waste pickers collecting materials from markets and dumps. Although this process contributes to income generation in vulnerable communities, the absence of consistent public policies and an organized reverse logistics infrastructure prevents the expansion of the sector and limits environmental benefits.

7 LEGISLATION AND QUALITY CONTROL IN MOZAMBIQUE

The Mozambican legal framework for food packaging is based on three main instruments: Decree No. 15/2006, which regulates the hygiene and labelling of foodstuffs; Ministerial Diploma No. 247/2011, which establishes mandatory labelling requirements for food products; and Ministerial Diploma No. 26/2025, which introduced the Environmental Tax on packaging, with the aim of encouraging sustainable practices.

The National Institute for Standardization and Quality (INNOQ) is the body responsible for implementing standards, assessing conformity and certifying products. The Conformity Assessment Program (PAC) requires certification of imported packaging and food, but its application faces practical difficulties. In addition, the shortage of specialized laboratories in the country limits the ability to perform migration assays and advanced analyses.

In practice, only large companies, such as Água da Namaacha, have been able to obtain international certifications such as ISO 22000, covering processes from production to packaging. Small and medium-sized companies, on the other hand, face obstacles related to the high cost and absence of accessible laboratory services, which highlights an urgent need for inclusion and strengthening of quality infrastructure in the country.

8 CONCLUSION

Food packaging is a strategic and multifunctional element in the production chain, acting not only in the protection and conservation of products, but also in transportation, communication and value addition. The review of metallic, plastic, glass, cellulosic and wood packaging materials shows that each type has advantages and limitations in terms of resistance, barrier to external agents, recyclability and suitability for local conditions in Mozambique.

The Mozambican context presents significant challenges, including dependence on imports, limited local production capacity, the absence of structured collection and recycling systems, as well as the scarcity of accredited laboratories for quality control and component migration tests. These factors result in high post-harvest losses, compromised food security, and restriction of the competitiveness of the agricultural and food sector.

Despite successful examples from large companies such as Cervejas de Moçambique, Água da Namaacha and logistics initiatives demonstrating the potential of sustainable practices and quality certification, there are still structural and regulatory gaps that limit the inclusion of small producers and traders.

Given this scenario, it is essential that Mozambique invests in strengthening the local packaging industry, technical training, the expansion of quality laboratories, and the implementation of public policies that promote sustainability, circular economy, and technological innovation. Only in this way will it be possible to reduce post-harvest losses, improve food security and increase the competitiveness of national products in the domestic and foreign markets.

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IONIZING RADIATION IN AGRICULTURE: PHYSICAL, BIOLOGICAL AND ONTOLOGICAL APPROACHES

RADIAÇÃO IONIZANTE NA AGRICULTURA: ABORDAGENS FÍSICAS, BIOLÓGICAS E ONTOLÓGICAS

RADIACIÓN IONIZANTE EN LA AGRICULTURA: ENFOQUES FÍSICOS, BIOLÓGICOS Y ONTOLÓGICOS

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ABSTRACT

Ionizing radiation has been present in agricultural and biological sciences for more than seven decades. Beyond its classical role in mutation breeding and food preservation, radiation has gained renewed attention as a tool for physiological stimulation at sublethal doses (a phenomenon known as radiohormesis). This chapter presents an integrative overview of the use of ionizing radiation in agriculture, addressing the physical principles, biological effects, and agronomic applications from a multidisciplinary perspective. Emphasis is placed on low-dose physiological responses, mechanisms of stimulation, and recent advances in digital knowledge systems that structure and disseminate information on radiobiological processes. The discussion aims to bridge traditional nuclear agronomy with modern approaches in ontology engineering and artificial intelligence for decision support.

Keywords: Ionizing Radiation. Agriculture. Mutation Breeding. Radiohormesis. Ontologies. Seed Physiology. Reproducibility.

RESUMO

A radiação ionizante tem estado presente nas ciências agrícolas e biológicas há mais de sete décadas. Além de seu papel clássico no melhoramento genético e na preservação de alimentos, a radiação tem recebido atenção renovada como ferramenta de estimulação fisiológica em doses subletais (fenômeno conhecido como radiohormese). Este capítulo apresenta uma visão integradora do uso da radiação ionizante na agricultura, abordando os princípios físicos, os efeitos biológicos e as aplicações agronômicas em uma perspectiva multidisciplinar. Dá-se ênfase às respostas fisiológicas de baixa dose, aos mecanismos de estimulação e aos avanços recentes em sistemas digitais de conhecimento que estruturam e disseminam informações sobre processos radiobiológicos. A discussão procura conectar a agronomia nuclear tradicional às abordagens modernas em engenharia ontológica e inteligência artificial voltadas ao apoio à decisão.

Palavras-chave: Radiação Ionizante. Agricultura. Melhoramento por Mutação. Radiohormese. Ontologias. Fisiologia de Sementes. Reprodutibilidade.

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RESUMEN
La radiación ionizante se ha utilizado en las ciencias agrícolas y biológicas durante más de siete décadas. Más allá de su papel clásico en la mejora genética y la conservación de alimentos, ha recibido renovada atención como herramienta para la estimulación fisiológica a dosis subletales (un fenómeno conocido como radiohormesis). Este capítulo presenta una visión integradora del uso de la radiación ionizante en la agricultura, abordando los principios físicos, los efectos biológicos y las aplicaciones agronómicas desde una perspectiva multidisciplinar. Se hace hincapié en las respuestas fisiológicas a bajas dosis, los mecanismos de estimulación y los avances recientes en sistemas de conocimiento digital que estructuran y difunden información sobre procesos radiobiológicos. El análisis busca conectar la agronomía nuclear tradicional con los enfoques modernos de la ingeniería ontológica y la inteligencia artificial, centrados en el apoyo a la toma de decisiones.

Palabras clave: Radiación Ionizante. Agricultura. Mejora por Mutación. Radiohormesis. Ontologías. Fisiología de las Semillas. Reproducibilidad.

1 INTRODUCTION

Ionizing radiation has played an important role in modern agronomy and plant biology since the mid-twentieth century. From the pioneering experiments of the early nuclear age, when controlled irradiation was first applied to crop seeds, scientists have explored radiation not only as a source of genetic variability but also as a physical agent capable of modifying metabolic and physiological processes in plants (VOSE, 1980). What began as an extension of atomic research into agriculture soon became one of the most productive intersections between physics and biology, giving rise to the field now known as *nuclear agronomy*.

Throughout the 1950s and 1960s, national and international programs (particularly those coordinated by the Food and Agriculture Organization (FAO) and the International Atomic Energy Agency (IAEA)) standardized the use of cobalt-60 and cesium-137 irradiators for seed treatment, mutation induction, and sterilization of pests. The FAO/IAEA joint division, established in 1964, became the main institutional driver for developing methodologies, dosimetry standards, and safety regulations (SPENCER-LOPES et al., 2018). Under this framework, hundreds of laboratories accross the world adopted irradiation as a practical technique for mutation breeding, phytosanitary treatment, and food preservation.

The agricultural applications of radiation evolved under two complementary paradigms that remain conceptually distinct yet mechanistically related: the *genetic paradigm* and the *physiological paradigm*. The genetic paradigm focuses on mutation breeding: the deliberate induction of heritable genetic variation through exposure to high or moderate doses of radiation, usually in the range of 100–400 Gy for most crops (SAVOV, 1989). This approach seeks to expand the genetic base of cultivated species, offering plant breeders new sources of allelic diversity that can be fixed by conventional selection and crossing. Over 3,400 officially released mutant varieties of cereals, legumes, ornamentals, and fruits have been developed worldwide using this method (FAO/IAEA, 2018).

The physiological paradigm, by contrast, deals with the short-term and (very) often non-heritable effects of low-dose irradiation on living tissues, particularly seeds and seedlings. In this context, radiation functions as a mild abiotic stressor capable of triggering adaptive responses at the molecular and cellular levels. When carefully calibrated, sublethal doses (typically below 20 Gy for most plant species) can accelerate germination, promote uniform emergence, and stimulate early biomass accumulation. This biphasic response, in which low doses enhance performance while higher exposures inhibit it, defines the phenomenon of *radiohormesis* (VILLEGAS et al., 2023). Although the term derives from the broader toxicological concept of hormesis, it has specific implications for plant physiology, suggesting that radiation may act as a priming factor that enhances vigor and stress resilience.

From a scientific perspective, these two paradigms represent different temporal and mechanistic scales of response. The genetic paradigm addresses changes in DNA sequence, chromosomal rearrangements, and mutation frequency: processes that require multiple generations of selection and stabilization. The physiological paradigm, on the other hand, operates on a much shorter timescale, modulating gene expression, antioxidant metabolism, and enzymatic activity without necessarily altering the genome. Yet both paradigms depend on the same fundamental interaction between ionizing energy and biological matter: the ionization of water molecules and the subsequent formation of reactive oxygen species (ROS), such as hydroxyl radicals, superoxide anions, and hydrogen peroxide (VOSE, 1980). These molecules, traditionally regarded as damaging agents, are now understood to function as key signaling intermediates when present in low concentrations.

The mechanistic link between oxidative signaling and beneficial physiological responses has been repeatedly demonstrated in controlled experiments. Sublethal irradiation doses generate transient increases in ROS, which in turn activate redox-sensitive transcription factors, mitogen-activated protein kinase (MAPK) cascades, and hormonal cross-talk pathways involving auxins, abscisic acid, and cytokinins (GENG et al., 2019). The activation of these pathways leads to faster mobilization of storage reserves, enhanced cell expansion, and earlier root and shoot initiation. When exposure exceeds the capacity of cellular antioxidant systems, however, oxidative stress dominates, resulting in lipid peroxidation, protein oxidation, and DNA strand breaks. This delicate balance between activation and inhibition defines the hormetic dose–response curve.

Empirical evidence for radiohormesis has accumulated across diverse species. Studies on cereals, legumes, and solanaceous crops report that gamma irradiation in the range of 5–15 Gy enhances germination rate, uniformity, and seedling vigor, while doses above 20 Gy generally suppress these traits (VILLEGAS et al., 2023). Controlled laboratory experiments with *Nicotiana tabacum* L. confirmed these trends, revealing varietal differences in sensitivity and optimum stimulation doses (ALVES et al., 2026). In those studies, low-dose gamma exposure (approximately 10–15 Gy) significantly advanced germination kinetics and increased early biomass, with the most responsive genotypes exhibiting up to 100% gains in fresh weight compared with non-irradiated controls. Importantly, the stimulatory window varied among cultivars, emphasizing that genetic background influences the balance between beneficial and deleterious outcomes. These findings corroborate earlier hypotheses proposed by (VOSE, 1980) that low-level radiation may serve as a developmental cue, analogous to mild temperature or osmotic stresses, capable of enhancing seed metabolic activity without structural damage.

Beyond its physiological effects, the use of radiation in agriculture intersects with broader questions of data standardization, reproducibility, and interdisciplinary knowledge management. For decades, experimental results on plant irradiation were disseminated through disparate sources (agronomy journals, radiobiology reports, and institutional bulletins) often using inconsistent terminology for dose units, biological endpoints, and material descriptions. As a result, integrating findings across species, laboratories, and irradiation conditions remains difficult. The emergence of ontological and digital knowledge frameworks seeks to address this fragmentation by providing formal structures to represent entities such as radiation source, dose range, and observed effect. Ontologies (machine-readable vocabularies that define relationships among concepts) enable interoperability between experimental databases and decision-support systems, paving the way for more systematic use of radiation data in agricultural research (ALVES et al., 2026).

Two complementary ontologies illustrate this trend. The first, OnTop, models the entire tobacco production lifecycle, integrating environmental, soil, and management factors relevant to agricultural decision support (ALVES et al., 2025). Although not limited to irradiation, it provides the conceptual foundation for integrating radiation effects within broader agronomic processes. The second, OnSIR (Ontology of Seed Irradiation), explicitly formalizes the domain of seed irradiation and plant radiobiology, capturing entities such as *StimulatoryDose*, *MutagenicRange*, and *SterilizationThreshold* (ALVES et al., 2026). By aligning radiation-related concepts with ontology engineering, OnSIR facilitates semantic queries such as “Which radiation ranges induce hormetic responses in *Nicotiana tabacum* for such-and-such variety?” or “What is the mutagenic range for dry soybean seeds?” This structured approach transforms experimental observations into machine-actionable knowledge, allowing integration with artificial intelligence systems for agricultural decision support.

From a historical standpoint, the institutionalization of radiation use in agriculture has followed a curious, quasi-Schopenhauerian cyclical pattern of enthusiasm and caution. The early decades emphasized mutation breeding and food sterilization, leading to notable achievements but also to public concern about radiation safety. Subsequent years witnessed a shift toward more conservative applications and stricter regulatory oversight. In recent years, however, advances in dosimetry, controlled facilities, and biological understanding have renewed interest in the beneficial uses of low-dose irradiation, supported by a clearer differentiation between ionizing radiation as a process and radioactivity as a property of matter. The adoption of rigorous safety protocols and the availability of compact gamma irradiators have made the technique accessible to agricultural research centers worldwide, including those in developing regions (FAO/IAEA, 2018).

The integration of classical radiobiological experimentation with modern data infrastructures marks a new phase in nuclear agronomy. Traditional studies provided invaluable empirical evidence on dose–response relationships and varietal sensitivity; contemporary ontological frameworks extend this legacy by ensuring that such knowledge remains discoverable, comparable, and reusable. The combined perspective (from the field experiment to the semantic model) encapsulates the evolution of radiation use in agriculture: from empirical observation to standardized science, and now to intelligent data-driven practice.

Therefore, the purpose of this chapter is to offer a comprehensive synthesis of these intertwined dimensions. It revisits the physical and biological foundations of ionizing radiation, surveys its classical and emerging agricultural applications, discusses the physiological basis of hormesis, and explores how semantic technologies and artificial intelligence can enhance knowledge integration and decision making in this field. By bridging the historical, experimental, and digital aspects of radiation agronomy, we aim to contextualize the enduring relevance of nuclear techniques in addressing contemporary agricultural challenges: productivity, sustainability, and scientific reproducibility.

2 PHYSICAL AND BIOLOGICAL FUNDAMENTALS OF IRRADIATION

2.1 NATURE OF IONIZING RADIATION

Ionizing radiation refers to any type of energy emission capable of removing electrons from atoms or molecules, generating ions and free radicals. It encompasses both electromagnetic waves of high frequency, such as gamma rays and X-rays, and particle radiation, such as electrons, protons, neutrons, or heavy ions. In agricultural applications, the predominant sources are gamma emitters derived from cobalt-60 (^{60}Co) and cesium-137

(^{137}Cs), as well as electron-beam accelerators used for low-penetration treatments (VOSE, 1980).

The suitability of each radiation type depends on penetration depth, dose rate, and interaction pattern. Gamma radiation offers high penetration and energy uniformity, allowing large sample volumes (such as seed batches or packaged products) to receive homogeneous exposure. Electrons, by contrast, have shallower penetration and are more appropriate for surface sterilization or thin biological materials. Ion beams and X-rays, while less common in agronomic settings, are important in experimental radiobiology for investigating high linear energy transfer (LET) effects and mutation spectra (SPENCER-LOPES et al., 2018).

From a physical standpoint, the absorbed dose (*D*) quantifies the amount of energy deposited per unit mass of material, expressed in gray (Gy), where $1\text{Gy}=1\text{Jkg}^{-1}$. However, dose alone does not fully describe biological impact; dose rate ($\text{Gy}\,\text{h}^{-1}$) and radiation quality (LET) are equally relevant. Low-LET radiation, such as gamma and X-rays, distributes ionizations sparsely, generating predominantly indirect effects mediated by reactive oxygen species (ROS). High-LET particles, such as alpha particles (particles identical to Helium nuclei) or heavy ions, produce dense ionization tracks, resulting in localized clusters of DNA damage (VOSE, 1980). These distinctions underlie the different biological responses observed among exposure types.

In agricultural facilities, dose uniformity and reproducibility are achieved through standardized geometries and calibration with dosimeters such as Fricke, ceric–cerous, or alanine systems. The FAO/IAEA protocols emphasize traceability of dose measurement, ensuring that each exposure is accompanied by detailed metadata including source strength, distance, temperature, and seed moisture content (FAO/IAEA, 2018). Such precision is essential when small variations in dose can shift a treatment from stimulatory to inhibitory.

Radiation in agriculture must also be understood as a controlled physical process, distinct from radioactivity in the sense of contamination. The energy delivered during exposure does not render the biological material radioactive, as the interaction involves energy transfer without nuclear transmutation (VOSE, 1980). This distinction, frequently misunderstood outside scientific circles, is crucial for public acceptance and regulatory approval of irradiated seeds or food products.

2.2 INTERACTION WITH BIOLOGICAL MATERIAL

The biological action of ionizing radiation begins with the absorption of energy by cellular components, especially water. In most plant tissues, water represents over 70% of the mass, making it the principal target of radiation. The ionization and excitation of water molecules produce a cascade of short-lived species (hydroxyl radicals ($OH\cdot$), hydrated electrons (e^-_{aq}), hydrogen atoms ($H\cdot$), hydrogen peroxide (H_2O_2), and molecular hydrogen (H_2)) collectively known as the products of water radiolysis (VOSE, 1980). The general sequence can be expressed as:

$$H_2O \xrightarrow{\text{radiation}} H\cdot, OH\cdot, e^-_{aq}, H_2, H_2O_2 \qquad (1)$$

These reactive intermediates diffuse within microseconds and interact with biomolecules such as lipids, proteins, and nucleic acids. Two main pathways of biological damage are recognized: (i) the *direct effect*, where radiation energy is deposited directly in macromolecules, causing ionization or excitation of the target itself; and (ii) the *indirect effect*, in which radicals generated in surrounding water react chemically with biomolecules. In hydrated tissues, indirect effects dominate, while in dry seeds, where free water is limited, direct energy deposition in the solid matrix becomes more significant (VOSE, 1980; SPENCER-LOPES et al., 2018).

At the cellular level, these reactions lead to a complex interplay of damage and signaling. Hydroxyl radicals can abstract hydrogen atoms from membrane lipids, initiating lipid peroxidation that alters membrane fluidity and permeability. Hydrogen peroxide, although less reactive, can diffuse through membranes and serve as a secondary messenger in redox signaling. In the nucleus, double-strand breaks (DSBs) in DNA are critical lesions that, if misrepaired, lead to mutations or chromosomal aberrations. However, at sublethal doses, the transient ROS burst acts as a signal that upregulates antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD), as well as DNA repair pathways (GENG et al., 2019). This paradoxical activation of defense and repair systems explains how mild irradiation can improve physiological performance.

A recent study by the authors on *Nicotiana tabacum* L. provides a quantitative illustration of this balance. When seeds were exposed to incremental doses between 0 and 20 Gy, stimulation of germination and biomass was observed in the 10–15 Gy range, whereas inhibition starts to appear beyond 15 Gy. The interpretation aligns with the radiolytic mechanism: within the stimulatory window, ROS concentrations are sufficient to activate metabolism but below the threshold of irreversible damage. As doses rise, ROS accumulation surpasses antioxidant capacity, leading to delayed germination and reduced growth. The study further confirmed that this dynamic differs among genotypes, underscoring the interaction between intrinsic radiosensitivity and oxidative metabolism (ALVES et al., 2026).

Radiation also affects the physical state of seed structures. In embryonic tissues, ionization can weaken cell wall cross-links and alter membrane potentials, facilitating water uptake during imbibition. Low doses may increase membrane permeability and stimulate respiratory activity, as evidenced by higher oxygen consumption rates in irradiated seeds (VOSE, 1980). Conversely, excessive ionization disrupts membranes, causing electrolyte leakage and impaired germination. In chloroplasts, gamma irradiation at the seedling stage influences pigment biosynthesis and photosynthetic efficiency, which can either enhance or reduce growth depending on dose and developmental timing.

2.3 DETERMINANTS OF RADIOSENSITIVITY

Radiosensitivity (the degree to which a biological system responds to a given radiation dose) varies widely among plant species, tissues, and physiological states. Several determinants govern this variability, encompassing physical, biochemical, and genetic factors (VOSE, 1980; SPENCER-LOPES et al., 2018).

1. Water Content and Physiological State.

Water content represents the most fundamental determinant. Dry seeds are considerably more resistant to irradiation than germinated or hydrated tissues because indirect damage mediated by water radiolysis is minimized. Under desiccated conditions, radicals formed within the solid matrix recombine locally before diffusing to sensitive targets. This explains why doses as high as 400 Gy can be used for mutation induction in dry seeds of cereals, whereas hydrated tissues exhibit lethal effects at one-tenth that level (VOSE, 1980). Conversely, in studies focused on physiological stimulation, partial hydration is often desirable, as a limited presence of free water enhances ROS-mediated signaling without reaching damaging concentrations (ALVES et al., 2026).

2. Genotype and Cellular Composition.

The genetic constitution of the plant determines baseline antioxidant capacity, DNA repair efficiency, and chromatin architecture, all of which influence radiation response. Varieties rich in phenolic antioxidants or possessing high SOD and CAT activity show extended hormetic windows. The *Nicotiana tabacum* varieties tested in controlled experiments exemplify this diversity: the Dark genotype exhibited maximal stimulation near 12.7 Gy, while the Burley and Virginia genotypes responded at slightly higher doses with lower amplitude. These distinctions likely arise from varietal differences in ROS metabolism and hormonal regulation (ALVES et al., 2026).

3. Dose Rate and Temporal Pattern.

The same total dose delivered at different rates can produce distinct biological outcomes. Low dose rates allow partial repair during exposure, whereas acute delivery generates higher instantaneous radical concentrations. FAO/IAEA guidelines recommend characterizing both absorbed dose and dose rate when reporting experiments to ensure comparability (SPENCER-LOPES et al., 2018). In mutation breeding, dose rates around 100–300 Gy h^{-1} are typical, while in radiohormesis experiments, much lower rates (1–10 Gy h^{-1}) are often employed to favor metabolic adaptation. This is one of the reasons why even "old" sources (i.e. sources where many half-lifes have passed) are useful for hormesis research.

4. Chromatin and Cell Cycle Stage.

The structural organization of chromatin influences the accessibility of DNA to damage and repair enzymes. Cells in active division, especially during G2 and mitosis, exhibit higher sensitivity due to chromatin condensation and lack of homologous repair templates. In multicellular plant tissues, meristematic regions are therefore the most radiosensitive. This principle guides practical irradiation protocols: dormant seeds or pollen are chosen for mutation breeding to reduce lethality, whereas sprouting tissues are targeted when the goal is to study metabolic stimulation (VOSE, 1980).

5. Environmental Modifiers.

Oxygen concentration, temperature, and the presence of chemical protectors or sensitizers modulate radiation effects. The so-called *oxygen enhancement ratio* (OER) quantifies how oxygen amplifies biological damage by stabilizing free radical species. Under hypoxic conditions, radical recombination is favored, reducing effective dose. Conversely, high oxygen availability enhances peroxidation and increases radiosensitivity (AVAKYAN et al., 1977). Temperature affects both radical diffusion and repair kinetics, with moderate heat accelerating enzymatic repair but excessive heat exacerbating stress.

6. Biological Endpoint and Measurement Criteria.

The interpretation of radiosensitivity also depends on the endpoint measured. For example, a dose that reduces final germination percentage may still improve germination rate or seedling vigor. Kinetic parameters such as the time to 50% germination (T_{50}) and the area under the germination curve (AUC) provide more sensitive indicators of hormetic stimulation than categorical survival data (ALVES et al., 2026). Understanding which physiological parameter best represents the desired effect is essential for consistent evaluation.

Integrating Physical and Biological Dimensions

The study of radiation effects in agriculture sits at the intersection of physics, chemistry, and biology. The absorbed dose, dose rate, and LET describe the physical side; the formation of radicals, antioxidant balance, and repair pathways describe the biological side. Bridging these domains requires a quantitative framework that links measurable exposure parameters to observable physiological outcomes. In this sense, recent ontological initiatives such as OnSIR formalize the connection between radiation physics and plant response by defining classes and relations like *Exposure*, *DoseCategory*, *BiologicalOutcome*, and *Radiosensitivity* (ALVES et al., 2026). These semantic structures translate empirical knowledge into computable form, enabling reasoning over diverse datasets.

The combined evidence from traditional radiobiology and contemporary data modeling converges on a coherent view: radiation acts as a modulator of biological systems whose effects depend on the fine balance between physical energy deposition and biochemical resilience. Understanding this duality is essential for designing irradiation treatments that are safe, reproducible, and beneficial. As emphasized by VOSE (1980, pp. 34–35), “the biological effect of radiation depends not only upon the total energy absorbed but upon the physical conditions of exposure and the physiological condition of the material irradiated,” and later (p. 146) he reiterated that “interpretation of plant responses to radiation must take into account both the physical characteristics of the exposure and the state of the organism at the time of treatment.” These statements remain as relevant today as when they were written, serving as a guiding principle for all subsequent research in nuclear agriculture.

2.4 CLASSICAL AGRICULTURAL APPLICATIONS

The use of ionizing radiation in agriculture emerged as an important component of post-war research into peaceful applications of atomic energy. Among its early successes were the induction of beneficial mutations in crops, the sterilization of insect pests for area-wide control programs, and the extension of food shelf life through inhibition of microbial growth and physiological decay. These practical outcomes established radiation as a versatile tool for both pre- and post-harvest stages of agricultural production. Despite being developed in the mid-twentieth century, these applications remain scientifically and economically relevant, forming the foundation for more recent studies on radiohormesis and precision irradiation (VOSE, 1980; FAO/IAEA, 2018).

2.5 MUTATION BREEDING

Mutation breeding represents the oldest and most institutionalized agricultural application of ionizing radiation. The principle is straightforward: exposing seeds, pollen, or vegetative tissues to a controlled dose of radiation increases the frequency of mutations, thereby generating novel genetic variability. In the end of the day, it is just the acceleration, "a little help", we may say, to the process Nature already does in evolution. This variability can then be exploited by conventional breeding techniques to select superior lines exhibiting desirable agronomic traits (SAVOV, 1989).

Historically, mutation induction was first demonstrated in 1927, when H. J. Muller showed that X-rays could produce heritable changes in *Drosophila*. By the 1930s, similar experiments on barley and maize had confirmed the mutagenic potential of radiation in plants. After the second World War, large-scale mutation programs were launched under the auspices of national atomic energy commissions and, later, through the FAO/IAEA Joint Division of Nuclear Techniques in Food and Agriculture. These initiatives standardized irradiation protocols, dosimetry methods, and breeding procedures, leading to the development of thousands of mutant cultivars across the globe (SPENCER-LOPES et al., 2018). They also helped rehabilitate nuclear science after the terrible crimes commited against Hiroshima and Nagasaki.

Typical doses for mutation breeding range from 100 to 400 Gy for dry seeds, depending on species radiosensitivity. The objective is to identify the so-called *semi-lethal dose* (LD_{50}), where about half the treated individuals survive and show a useful mutation frequency without excessive lethality (VOSE, 1980). In cereals such as rice and barley, LD_{50} usually lies between 200 and 300 Gy; in legumes, around 150–250 Gy; and in vegetatively propagated crops, even lower doses may be required. Mutations are typically point changes or small deletions, although chromosomal rearrangements and translocations can also occur. The resulting phenotypic diversity is enormous: altered plant architecture, modified seed color, enhanced disease resistance, or improved abiotic stress tolerance may occur.

By 2018, the FAO/IAEA Mutant Variety Database listed more than 3,400 officially released mutant varieties worldwide, including major staples such as rice, wheat, barley, and soybean, as well as fruits and ornamentals (FAO/IAEA, 2018). The global impact is substantial: in China, mutation breeding contributed to more than one million hectares of improved rice cultivars; in Japan, the famous “Reimei” rice, derived from gamma-irradiated material, marked a milestone in food security; and in Latin America, radiation-induced mutants of beans and groundnuts have shown enhanced yield stability under semi-arid conditions.

Methodological refinements have expanded the range of mutagenic materials and target tissues. Beyond seeds, scientists now use in vitro culture systems (such as callus, somatic embryos, and micropropagated shoots) allowing greater control over mutation spectrum and chimerism. The advent of molecular markers and genomic sequencing has also enabled the identification of specific mutations and the mapping of radiation-induced alleles, thereby improving selection efficiency. These molecular approaches confirm Vose’s (1980) prediction that radiation, as a tool of mutation induction, will achieve its greatest potential when combined with biochemical and genetic screening techniques.

Mutation breeding programs follow a structured sequence: (1) determination of radiosensitivity curve and optimal dose, (2) mass irradiation of seeds or tissues, (3) cultivation of the M_1 generation to identify surviving plants, (4) selection of variants in subsequent generations (M_2–M_4), and (5) agronomic evaluation and stabilization of promising mutants. Each step requires careful record keeping of irradiation parameters, emphasizing dose rate, seed moisture, and post-irradiation storage conditions. Recent ontological models, such as the OnSIR framework, formalize this workflow, defining classes like *ExposureProcess*, *MutationInduction*, and *PhenotypicScreening*, which help integrate diverse experimental datasets into consistent digital repositories (ALVES et al., 2026).

While mutation breeding relies on relatively high doses, the biological mechanisms involved share continuity with those operating at lower doses. Both rely on the initial ionization of cellular components and the activation of repair and signaling pathways. In fact, the threshold between mutagenic and hormetic responses may depend more on repair fidelity and dose accumulation than on qualitatively different processes. Thus, mutation breeding and radiohormesis can be viewed as opposite ends of a continuous spectrum of radiation–plant interactions.

2.6 PHYTOSANITARY TREATMENT

Beyond its use for genetic improvement, ionizing radiation provides a powerful means of controlling pests and pathogens in agricultural commodities. The concept of using radiation for disinfestation was introduced shortly after its application in mutation breeding. The method exploits the differential radiosensitivity between microorganisms and the treated product: doses sufficient to eliminate (or inactivate in the case of spores) insects or fungi are far below those that could damage plant tissue or alter food quality (VOSE, 1980).

Phytosanitary irradiation involves exposing harvested commodities (grains, fruits, nuts, spices, or leaves) to doses typically ranging from 200 to a few thousand Gy. The biological effects include inhibition of cell division in insects, sterilization of reproductive organs, and suppression of fungal sporulation. The process leaves no chemical residues and does not significantly increase product temperature, making it environmentally safe and compatible with international trade standards (WARKE et al., 1999). Usually, also, organoleptic characteristics are maintained after processing.

Radiation-based pest control operates through several mechanisms. In insects, gamma irradiation induces dominant lethal mutations, preventing reproduction. In fungi and bacteria, DNA strand breaks and oxidative damage inhibit replication. Because the treated commodities are metabolically quiescent, such doses cause negligible structural or biochemical alterations in the host tissues. The FAO/IAEA and the International Plant Protection Convention (IPPC) recognize phytosanitary irradiation as an approved method for quarantine treatment, allowing countries to meet biosecurity requirements without relying on methyl bromide or phosphine fumigation (FAO/IAEA, 2018).

An illustrative example is the use of gamma irradiation for the control of storage pests such as *Sitophilus oryzae* (rice weevil) and *Callosobruchus maculatus* (cowpea beetle). Doses of 300–600 Gy effectively sterilize adult insects without affecting grain viability or nutritional value. In the tobacco industry, irradiation has been successfully employed to reduce microbial contamination and insect infestation in processed leaves, improving hygienic quality while preserving organoleptic characteristics (WARKE et al., 1999). This approach aligns with sustainable production goals and consumer safety, as no pesticide residues are involved.

Modern advances extend these concepts to integrated pest management (IPM) strategies, combining irradiation with biological control agents and environmental monitoring. For instance, sterile insect technique (SIT) programs employ radiation to sterilize male insects before release into target populations, reducing reproduction rates in pest species such as fruit flies and tsetse flies. These programs illustrate how radiation can serve not merely as a disinfestation method but as a relevant part of ecological pest control, reducing chemical dependence and environmental impact.

Ontological frameworks such as OnTop contribute to the management of phytosanitary data by structuring information about pest species, treatment parameters, and environmental conditions (ALVES et al., 2025). Within such systems, the concept of *ManagementAction* encompasses activities like irradiation, fumigation, or thermal treatment, allowing interoperability between datasets from different regulatory and experimental sources. This digital structuring of phytosanitary knowledge enhances traceability, compliance verification, and the optimization of treatment protocols.

Food Preservation

A third major application of ionizing radiation in agriculture and food science is the preservation of perishable products. While mutation breeding and phytosanitary control operate at relatively higher doses, food preservation relies on comparatively low exposures (generally between 50 and 150 Gy) sufficient to inhibit sprouting, delay ripening, and suppress enzymatic activity without altering sensory or nutritional attributes (FAO/IAEA, 2018).

The physiological processes leading to spoilage or deterioration are largely enzymatic or hormonal in nature. After harvest, tubers such as potatoes and onions may sprout, consuming stored carbohydrates and reducing market value. Similarly, enzymatic browning in fruits and microbial growth in spices compromise appearance, taste and safety. Ionizing radiation interrupts these processes by inhibiting cell division in meristematic tissues and inactivating oxidative enzymes like polyphenol oxidase (PPO) and peroxidase (POD). The result is prolonged shelf life and improved product uniformity.

Radiation preservation differs fundamentally from thermal or chemical methods. Because the absorbed energy is low and evenly distributed, temperature rise during treatment rarely exceeds 1–2°C, avoiding the loss of volatile compounds and vitamins. Moreover, unlike chemical preservatives, radiation leaves no residues and requires no additives, an advantage for health-conscious consumers. The FAO and WHO have repeatedly affirmed the safety of irradiated foods when processed under recommended guidelines (FAO/IAEA, 2018).

Numerous case studies demonstrate these benefits. In potatoes, doses around 100 Gy inhibit sprouting for several months without affecting cooking quality. In onions, similar doses prevent sprouting and extend storage life by 4–6 months. Mangoes and papayas irradiated with 100–200 Gy maintain firmness and color longer during export, reducing post-harvest losses. In spices such as pepper and cardamom, gamma irradiation at 5–10 kGy ensures microbial decontamination while preserving aroma and flavor. Although higher than the doses used for physiological preservation, such treatments remain well below thresholds that induce chemical or nutritional degradation (VOSE, 1980).

From an operational standpoint, food irradiation requires precise dosimetry and validation. Factors such as packaging material, product density, and moisture content influence dose distribution. To ensure compliance, dosimeters are placed at minimum and maximum dose locations within the product lot, and absorbed doses are verified against established standards. International guidelines specify labeling requirements and recommend the use of the “Radura” symbol to identify irradiated foods, promoting transparency and consumer confidence.

The integration of food preservation data into digital frameworks further exemplifies the evolution of radiation technology toward smart agriculture. By linking parameters like dose, temperature, and microbial load within an ontological model, researchers can build predictive systems to optimize treatment schedules and logistics. For example, a knowledge graph could relate *IrradiationDose* to *ShelfLifeExtension* and *MicrobialReduction*, enabling automated reasoning about ideal storage conditions and trade routes (ALVES et al., 2025).

Broader Significance and Legacy

The classical applications of radiation (mutation breeding, phytosanitary control, and food preservation) collectively illustrate the versatility of ionizing energy in addressing diverse agricultural challenges. They also exemplify the transition from empirical experimentation to standardized technological practice. Each application involves the same fundamental physics but distinct biological targets: in mutation breeding, DNA within developing embryos; in phytosanitary treatments, the reproductive cells of pests and pathogens; and in food preservation, the metabolic enzymes of harvested tissues. The range of effective doses across these applications spans nearly four orders of magnitude, from a few tens to several thousand gray, underscoring the importance of precise dosimetry and contextual interpretation (VOSE, 1980).

These achievements paved the way for contemporary investigations into low-dose effects and radiohormesis. As noted in recent studies on *Nicotiana tabacum*, physiological stimulation occurs at doses an order of magnitude lower than those used for mutation induction but within the same conceptual framework of radiation–biomolecule interaction (ALVES et al., 2026).

Furthermore, the classical applications demonstrate that radiation can be a sustainable technology when integrated responsibly. Unlike chemical fumigants or thermal sterilization, irradiation consumes relatively little energy, produces no greenhouse gases, and generates no hazardous waste. It aligns with the United Nations Sustainable Development Goals (SDGs), particularly those concerning responsible consumption, zero hunger, and climate action. In this sense, the legacy of the early nuclear agronomy programs continues to evolve: from the initial promise of atomic progress to the modern vision of intelligent, low-impact agriculture.

Table 1

Summary of ionizing radiation dose ranges and their main agricultural purposes, aligned with mechanistic interpretation and ontological classes.

Effect / Application	Typical Dose Range (Gy)	Purpose / Biological Effect	Consistency and Mechanistic Notes
Hormesis (Low-dose Stimulation)	Below 20, optimum 5–15	Enhances germination, vigor, antioxidant activity (SOD, CAT, POD), and early biomass. Acts as seed priming via mild ROS signaling and hormonal modulation.	Consistent with *N. tabacum* optima ($\approx 12.5 Gy$) and FAO/IAEA reports (5–15 Gy). Represented in **OnSIR: StimulatoryDose**. (VOSE, 1980; ALVES et al., 2026; VILLEGAS et al., 2023)
Mutagenesis (Breeding)	100–400 (dry seeds)	Induces heritable variation for selection (yield, stress resistance).	Aligned with VOSE (1980) and FAO/IAEA (2018) values: cereals 200–300, legumes

Effect / Application	Typical Dose Range (Gy)	Purpose / Biological Effect	Consistency and Mechanistic Notes
		Used to determine LD_{50}.	150–250. Mechanism: DNA double-strand breaks and imperfect repair. **OnSIR: MutagenicRange**. (SAVOV, 1989)
Phytosanitary / Sterilization	200–1000 (pests); 5–10 kGy (spices)	Eliminates insects, fungi, bacteria; replaces fumigants for quarantine and microbial safety.	Mechanisms: dominant lethal mutations, inhibition of sporulation. Consistent with VOSE (1980), WARKE et al. (1999). **OnSIR: SterilizationThreshold**.
Food Preservation	50–150	Inhibits sprouting and enzymatic browning; prolongs shelf life of tubers and fruits.	FAO/IAEA (2018): potatoes, onions, mangoes, papayas. Mechanism: inhibition of mitosis in meristematic tissues. **OnSIR: InhibitoryDose**.
Industrial Sterilization	10–25 kGy	Complete microbial inactivation (media, medical/food).	Above physiological range; causes macromolecule degradation. Retains relevance for in vitro seed sterilization. **OnSIR: HighDoseRange**.

Low-Dose Effects and Radiohormesis

At sublethal doses (typically 1–20 Gy), ionizing radiation may stimulate metabolic activity, accelerate germination, and enhance early seedling performance. This biphasic dose–response relationship (where low doses produce beneficial stimulation and higher doses inhibit or damage) is termed *radiohormesis*. The concept, long debated in toxicology, has gained renewed attention in plant sciences as a possible tool for sustainable crop improvement (VOSE, 1980; VILLEGAS et al., 2023).

Radiation hormesis represents a paradoxical biological response: the same agent capable of inducing DNA damage and growth inhibition at high intensities can, at lower levels, activate protective and adaptive mechanisms that ultimately improve vitality. The recognition of this phenomenon in plants has transformed how agronomists interpret radiation effects (from strictly deleterious to potentially regulatory) and has opened a new frontier in seed technology, stress physiology, and digital agronomy (ALVES et al., 2026).

Physiological Basis

The physiological basis of radiohormesis lies in the interplay between stress perception and adaptive response. Ionizing radiation interacts with plant cells primarily through the radiolysis of water, producing reactive oxygen species (ROS) such as hydroxyl radicals, superoxide anions, and hydrogen peroxide. At high doses, these radicals accumulate to cytotoxic levels, causing membrane peroxidation, enzyme inhibition, and DNA strand breaks. At low doses, however, the transient increase in ROS serves as a signal that activates redox-sensitive transcription factors, enzymatic defense systems and hormonal pathways (VOSE, 1980).

Experimental evidence indicates that the ROS burst following low-dose irradiation functions similarly to the oxidative signaling observed during seed priming with osmotic or vernalization treatments. The elevated redox potential triggers NADPH-dependent enzymes, increases ATP turnover, and mobilizes reserve compounds. Enzymes such as amylase, peroxidase, and catalase exhibit enhanced activity within hours after exposure, facilitating faster energy release for germination (GENG et al., 2019). The upregulation of superoxide dismutase (SOD) and catalase (CAT) ensures rapid neutralization of excess radicals, preventing oxidative damage while maintaining a mild stress signal.

At the subcellular level, mitochondria and chloroplasts play critical roles in this adaptive response. Low doses of radiation have been shown to increase mitochondrial respiration rates and chlorophyll biosynthesis in young seedlings. Such responses suggest a temporary enhancement of metabolic flux, consistent with the "overcompensation" model of hormesis proposed by Calabrese and Baldwin (2003), in which mild stress elicits compensatory processes that exceed basal levels of function.

Hormonal modulation further contributes to the stimulatory effects. Studies in *Nicotiana tabacum* and other species show that low-dose gamma irradiation elevates auxin and cytokinin levels while transiently suppressing abscisic acid (ABA), thereby promoting cell division and elongation (VOSE, 1980). Irradiation also influences calcium signaling, a key mediator in stress perception, which in turn regulates antioxidant enzyme gene expression. The cumulative effect of these pathways manifests as enhanced germination rate, improved uniformity, and increased early biomass accumulation.

Recent insights suggest that radiohormetic signaling may involve epigenetic mechanisms as well. DNA methylation, histone modification, and microRNA regulation have all been implicated in the adaptive memory induced by mild radiation stress (ALVES et al., 2026). Such modifications can persist across cell divisions, offering a plausible explanation for the sustained improvement in vigor observed in irradiated plants beyond the immediate treatment phase.

Experimental Evidence

Over seven decades of experimentation have established radiohormesis as a reproducible though dose-sensitive phenomenon. Early observations by VOSE (1980) described enhanced germination and growth in barley and lettuce irradiated at 5–10 Gy, followed by inhibition above 20 Gy. Subsequent FAO/IAEA trials across multiple species confirmed that the stimulatory window generally falls between 5 and 15 Gy for dry or semi-dry seeds (FAO/IAEA, 2018). Within this range, germination speed, seedling height, and chlorophyll content often surpass those of non-irradiated controls.

Controlled experiments with *Nicotiana tabacum* L. have provided one of the most detailed analyses of this effect. In a recent study by the authors, three commercial varieties (Burley, Dark and Virginia) were exposed to graded doses from 0 to 20 Gy using a ^{60}Co gamma source. Measurements included germination kinetics, seedling dry mass, and growth rate over two and four weeks. Results revealed clear varietal differences in sensitivity: the Dark variety exhibited maximal stimulation near 12.5 Gy, with biomass increases exceeding 100% relative to control, while BY and VA showed smaller yet significant gains around 10 Gy. Above 15 Gy, growth declined, confirming the narrowness of the hormetic window (ALVES et al., 2026). The main germination kinetics and biomass parameters are presented in Table 2.

Table 2

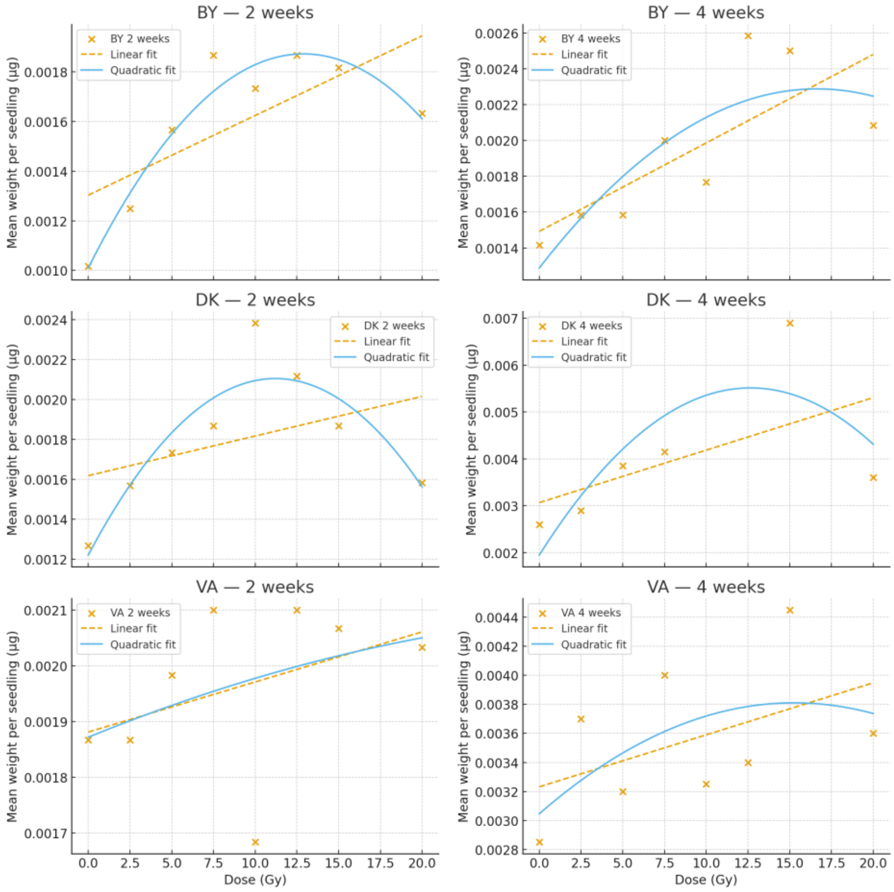
Mean germination and biomass parameters for three Nicotiana tabacum varieties exposed to graded doses of gamma radiation. Adapted from ALVES et al. (2026).

Variety	Dose (Gy)	T_{50} (days)	AUC (a.u.)	Biomass Change (%)
Burley (BY)	0–20	3.8–3.1	92–110	+45
Dark (DK)	0–20	4.0–2.9	88–121	+112
Virginia (VA)	0–20	3.6–3.2	95–107	+38

As shown in Figure 1, the dose–response curves for seedling biomass exhibit a distinct biphasic pattern: growth enhancement up to 15 Gy followed by a decline at higher exposures. This figure illustrates the quantitative transition from stimulation to inhibition, reinforcing the concept that radiosensitivity and adaptive repair capacity define the effective range of radiohormesis in plants (ALVES et al., 2025).

Figure 1

Dose–response curves for seedling biomass in three Nicotiana tabacum varieties after gamma irradiation. The range 10–15 Gy corresponds to the stimulatory window identified experimentally.



Source: From ALVES et al. (2026).

Kinetic analyses based on time-to-50% germination (T_{50}) and area under the germination curve (AUC) provided quantitative indicators of stimulation. Low doses reduced T_{50} by up to 30%, signifying faster emergence, and increased AUC values, reflecting more uniform population establishment. These physiological improvements correlated with increased antioxidant enzyme activities and higher soluble sugar concentrations in the cotyledons, supporting the hypothesis that mild oxidative stress accelerates reserve mobilization.

Other species exhibit similar biphasic patterns. In cowpea and soybean, irradiation at 5–10 Gy enhanced germination percentage and vigor index, whereas doses beyond 20 Gy reduced root and shoot lengths (GENG et al., 2019). In wheat, stimulation of seedling height and chlorophyll content occurred at 8 Gy, with inhibition above 25 Gy. In tomato, low-dose gamma irradiation improved early growth and photosynthetic efficiency but delayed flowering when exposure exceeded 15 Gy (WIENDL, 2010). Such consistency across taxa supports the generality of the hormetic model in plants, although the optimal dose varies by genotype, seed moisture and dose rate.

The reproducibility of radiohormesis depends critically on dosimetric precision and environmental control. Small deviations in absorbed dose or humidity can shift the stimulatory range. The FAO/IAEA recommends that researchers characterize the full dose–response curve for each species under well-defined conditions, including seed moisture content, oxygen availability, and post-irradiation storage time (FAO/IAEA, 2018). These parameters determine the balance between ROS generation and antioxidant capacity, which ultimately dictates whether stimulation or inhibition occurs.

Ontological frameworks such as OnSIR formalize this relationship by defining explicit classes like *LowDoseRange*, *StimulatoryDose*, and *InhibitoryDose* (ALVES et al., 2026). Through logical relations such as LowDoseRange ⊆ hasEffect some (StimulatesGrowth or EnhancesGermination), the ontology enables computational reasoning about experimental outcomes. Aligning these formal definitions with data from radiation facilities, the system supports meta-analyses across species and dose categories, facilitating the identification of generalized hormetic thresholds.

Mechanistic Insights

Understanding why plants exhibit hormesis requires reconciling molecular events with whole-organism outcomes. Three complementary hypotheses dominate current explanations.

First, the *adaptive repair hypothesis* posits that low-dose irradiation activates DNA repair systems more robustly than they are required at baseline. The transient activation of these pathways not only corrects minor damage from the exposure itself but also preconditions the cell against future stress. Enhanced activity of enzymes involved in base excision repair (BER) and nucleotide excision repair (NER) has been documented in irradiated seedlings (VOSE, 1980).

Second, the *metabolic stimulation hypothesis* suggests that mild radiation acts as an energy catalyst by accelerating respiratory metabolism. Measurements of oxygen consumption and dehydrogenase activity show short-term increases after low-dose exposure, leading to greater ATP availability for cell division and elongation (GENG et al., 2019). The increase in metabolic rate, however, declines after several days, indicating that the stimulation is transient and self-limiting.

Third, the *signaling balance hypothesis* integrates ROS and hormonal signaling into a unified model. According to this view, ROS generated by radiolysis serve as primary messengers that modulate calcium influx and activate protein kinases. These signals, in turn, alter transcriptional networks governing antioxidant defenses and growth regulation. The resulting dynamic equilibrium produces enhanced physiological performance without lasting oxidative damage.

Epigenetic studies provide additional evidence for a “memory effect” of low-dose irradiation. Methylation-sensitive markers reveal temporary changes in DNA methylation patterns following sublethal exposure, some of which persist through early development. Such reversible epigenetic reprogramming may underlie the enhanced vigor observed in seedlings derived from irradiated seeds (ALVES et al., 2026).

Agronomic Implications

The recognition of radiohormesis has significant agronomic implications. Low-dose irradiation can be regarded as a form of *physical seed priming*, analogous to hydropriming or osmopriming but achieved through energy transfer rather than chemical or osmotic gradients. The method offers unique advantages: uniform treatment of large seed batches, independence from water quality, and compatibility with existing gamma facilities used for mutation breeding (FAO/IAEA, 2018).

Potential applications include:

- *Enhancement of germination under stress:* Irradiated seeds often show improved emergence in saline, drought, or temperature-stressed soils. The pre-activation of antioxidant systems increases tolerance to oxidative stress encountered during germination.
- *Synchronization of seedling establishment:* More uniform germination leads to homogenous crop stands, facilitating mechanized management and reducing yield variability.
- *Stimulation of early vigor:* Accelerated growth at the seedling stage can improve competitiveness against weeds (an often overlooked advantage) and contribute to better resource use efficiency.

However, practical implementation requires rigorous standardization. Unlike mutation breeding, where small variations in dose can be tolerated, radiohormetic effects depend on precise calibration. Environmental factors such as relative humidity, oxygen concentration, and storage period between irradiation and sowing can modulate outcomes dramatically. Excessive delay between treatment and planting may allow ROS-related signaling effects to dissipate, reducing stimulation (VOSE, 1980).

To address these challenges, FAO/IAEA protocols recommend detailed reporting of physical and biological parameters. Ontological data models now incorporate such metadata under standardized properties like *hasDoseRate*, *hasMoistureCondition*, and *hasPostTreatmentInterval*, ensuring that future analyses can compare results reproducibly (ALVES et al., 2026). The use of semantic frameworks is thus instrumental for transforming radiohormesis from a qualitative observation into a quantitatively predictable process.

In the broader context of sustainable agriculture, radiation-induced seed priming aligns with the goals of reducing chemical inputs and enhancing resilience. It requires no additives, generates no waste, and can be performed in facilities already available for food irradiation. Furthermore, when integrated with digital monitoring and decision-support systems, radiohormesis data can feed into predictive models that optimize planting schedules based on environmental conditions and seed vigor (ALVES et al., 2025). This synthesis of physical treatment, biological response, and digital reasoning exemplifies the evolution of nuclear techniques into components of intelligent agronomy.

Challenges and Perspectives

Despite compelling evidence, several challenges limit the broader adoption of radiohormesis in agricultural practice. The first is *variability*. Results often differ among laboratories due to small deviations in dose measurement or seed condition. This variability underscores the need for harmonized methodologies and inter-laboratory calibration campaigns, similar to those established for mutation breeding (FAO/IAEA, 2018).

The second challenge is *mechanistic uncertainty*. Although the involvement of ROS signaling is well supported, the precise molecular events linking radiation exposure to developmental acceleration remain incompletely understood. Integrating omics approaches (transcriptomics, proteomics and metabolomics) with traditional physiology could possibly clarify these pathways. Ontological modeling provides a formal framework for organizing such complex, multiscale data.

A third challenge concerns *public perception*. The term “radiation” continues to evoke apprehension despite the absence of induced radioactivity or chemical residues in irradiated materials. Effective science communication, emphasizing safety and environmental benefits, is essential to foster acceptance among producers and consumers. The historical success of food irradiation programs demonstrates that these concerns can be overcome through transparency and regulatory oversight.

Looking forward, advances in precision dosimetry, automated irradiation systems, and AI-driven experimental design promise to enhance reproducibility and scalability. The combination of low-dose gamma irradiation with other priming techniques (for instance, hydropriming, vernalization or magnetic field treatment) may yield synergistic benefits. From a data perspective, the linkage of radiation exposure parameters with agronomic outcomes through semantic databases will allow predictive modeling of hormetic windows for diverse species and environments (ALVES et al., 2026).

Digital and Ontological Approaches in Radiation Agronomy

Need for Knowledge Integration

Although the use of ionizing radiation in agriculture dates back more than seventy years, the accumulated knowledge in plant radiobiology remains dispersed across thousands of reports, theses and localized experiments. Many of these studies were conducted independently, using different experimental setups, units of measurement, and biological descriptors. As a result, comparative synthesis and meta-analysis are often difficult or impossible. For example, two laboratories might report “seed stimulation” at 10 Gy in distinct species but measure outcomes with incompatible metrics: one as germination percentage, another as biomass gain. Without shared standards for terminology and metadata, cross-study interpretation remains largely qualitative (FAO/IAEA, 2018).

This fragmentation reflects a historical pattern in agricultural research, where local adaptation of methods and terminology evolves faster than formal standardization. In the specific field of plant irradiation, the problem is amplified by interdisciplinary complexity: physics defines exposure in terms of absorbed dose and linear energy transfer, while agronomy expresses results through growth indices, yield or stress tolerance. Bridging these vocabularies requires an explicit mapping between physical and biological parameters, a task that cannot rely solely on narrative description.

In recent years, the convergence of agricultural informatics, data science, and ontology engineering has provided new tools for solving this integration gap. An ontology, in its simplest sense, is a structured representation of knowledge: a vocabulary of concepts and relationships formalized so that humans and computers can interpret data consistently. In radiation agronomy, this means formally representing entities such as *radiation source*, *dose* *category*, *biological material* and *observed effect* (ALVES et al., 2026). Ontological models allow the results of field or laboratory experiments to be described not as isolated text, but as standardized data points linked to a conceptual framework. Once structured this way, data can be reused, compared, and analyzed automatically.

The motivation for such integration is practical. Modern agricultural research increasingly relies on data sharing among institutions, long-term monitoring, and meta-analytical modeling. Precision agriculture and climate-smart farming already employ semantic databases to integrate information on soil, weather, and crop management. Extending this digital infrastructure to encompass radiation effects ensures that the empirical foundation of nuclear agronomy becomes interoperable with the broader agricultural knowledge ecosystem. By connecting radiation response data to soil fertility, climate, and management practices, scientists can explore questions such as: “Under which climatic conditions is low-dose irradiation most beneficial for germination?” or “How does seed moisture interact with radiation to affect field emergence?” Such questions require structured, multi-dimensional data that only semantic frameworks can consistently support.

Ontologies as Semantic Infrastructure

Ontologies differ from simple databases because they represent not only data but also meaning. Each concept in an ontology belongs to a hierarchy, has defined properties, and is linked to others through explicit relationships such as *is a type of*, *has dose*, *causes effect* or *occurs in species*. This structure enables machines to perform reasoning (to infer new information from existing statements) and allows humans to interpret complex datasets without ambiguity (ALVES et al., 2026).

In radiation agronomy, several conceptual layers must be integrated. At the physical level, irradiation is described by parameters such as energy, dose, and dose rate. At the biological level, outcomes are classified as mutation, stimulation, or inhibition. Between them lies an intermediate layer of experimental context: species, variety, tissue type, water content, and environmental conditions. Ontologies provide the scaffolding to connect these layers, enabling queries such as:

“Which species exhibit stimulatory effects between 5 and 10 Gy of gamma radiation when seed moisture is below 12%?”

Such a query requires the ontology to know that *gamma radiation* is a subclass of *ionizing radiation*, that *5–10 Gy* corresponds to a *low-dose range*, and that *seed moisture* is an environmental modifier of radiosensitivity. Without this semantic infrastructure, answering such a question would require manual review of dozens of papers.

The Ontology for Seed Irradiation (OnSIR) was designed to formalize exactly this type of knowledge (ALVES et al., 2026). OnSIR represents the conceptual domain of seed irradiation through classes such as *Exposure*, *DoseCategory*, *RadiationSource*, *BiologicalMaterial*, and *Outcome*. It distinguishes categories like *StimulatoryDose*, *MutagenicRange*, and *SterilizationThreshold*, allowing precise annotation of experimental data. In this framework, the 10–15 Gy range that stimulates germination in *Nicotiana tabacum* L. is formally defined as a subclass of *LowDoseRange* that has the property *induces* some *EnhancedGermination*. This formalization transforms a qualitative observation into a structured assertion that can be queried or compared automatically.

Another layer of semantic modeling is provided by the Ontology of Tobacco Production (OnTop), which focuses on the agronomic side of the crop system (ALVES et al., 2025). OnTop models entities such as *ClimateCondition*, *SoilCondition*, *ManagementAction*, and *YieldOutcome*. When linked to OnSIR, it allows radiation treatments to be interpreted within the broader production cycle: for instance, how seedbed irradiation affects subsequent field growth or curing quality. Through such linkage, ontologies act as bridges between laboratory radiobiology and real-world agricultural management.

Beyond individual ontologies, the principle of interoperability is central. Agricultural research increasingly adopts shared, ensuring that new domain-specific vocabularies can communicate with existing ones. OnSIR follows this approach, aligning its classes with higher-level categories like *Process*, *MaterialEntity*, and *Quality*. As a result, its data can interact with environmental and crop ontologies without semantic conflict, promoting the integration of radiation effects into global agricultural data infrastructures.

For agricultural scientists, the value of such semantic infrastructure lies not in abstract logic but in practical benefits: reproducibility, discoverability, and decision support. When radiation experiments are described using standardized ontological terms, other researchers can reproduce treatments with confidence, knowing exactly what dose range, environmental condition and biological material were used. Moreover, digital repositories indexed by ontological terms allow future studies to build on existing results without redundancy (something that every researcher in this field has encountered).

Application in Agricultural Research and Extension

The agricultural implications of ontology-based systems extend beyond the laboratory. In breeding programs, radiation is used not only to induce mutations but also to evaluate stress tolerance. Ontological data models can document the full experimental workflow, from irradiation to field performance, capturing metadata such as irradiation facility, date, dose rate, variety name, and observed trait. This structured documentation becomes invaluable when evaluating long-term responses or correlating radiation treatments with climatic variability (ALVES et al., 2025).

In extension and production systems, semantic databases can assist in knowledge transfer. For example, an agricultural advisor might query a digital platform for recommended irradiation doses to stimulate germination in tobacco or cowpea under specific moisture conditions. The system, drawing from ontologically structured data, can provide evidence-based guidelines along with safety and operational parameters. By embedding radiation knowledge into the digital tools already used in precision agriculture, ontologies make nuclear techniques accessible to practitioners who may have no formal training in radiobiology.

Another promising application is the integration of irradiation data with environmental and phenological monitoring. Linking OnSIR concepts like *DoseRate* and *ExposureTime* to OnTop entities such as *Temperature*, *Humidity*, or *SoilMoisture* allows researchers to model how environmental variables modulate radiation effects. For instance, the same 10 Gy dose may produce stronger stimulation under moderate humidity than under arid conditions, due to differences in ROS diffusion and seed hydration. By embedding these relationships into an ontology, the system can generate hypotheses and guide future experiments.

Integration with Artificial Intelligence

While ontologies provide the formal backbone of knowledge, artificial intelligence (AI) tools offer the reasoning capacity to make this knowledge operational. Large Language Models (LLMs), when integrated with ontological data, can generate coherent explanations and recommendations that combine symbolic precision with linguistic flexibility. In practice, this means that an AI system trained on agricultural data can understand user questions like "What is the optimal irradiation dose for stimulating tobacco seed germination at such-and-such latitude and longitude for such-and-such variety at such-and-such time of the year?" and consult structured ontological knowledge to refine its answer (ALVES et al., 2026).

This hybrid approach was tested in experimental evaluations where an LLM was provided with and without access to ontologies, with promising results.

From an agricultural viewpoint, AI–ontology integration offers practical advantages. It can support decision-making in seed technology, quality assurance, and training. In seed processing facilities, an AI assistant equipped with OnSIR data could recommend irradiation settings according to crop type and moisture level. In extension services, digital platforms could answer farmer queries about the safety and benefits of irradiated seeds, ensuring accurate information dissemination and reducing misconceptions about radiation use in agriculture.

Importantly, the goal of such systems is not to replace expert judgment but to complement it. Ontologies capture consensus knowledge, while AI provides interpretative flexibility. Together, they can democratize access to complex scientific information, bridging the gap between nuclear research centers and agricultural communities. This synergy aligns with the FAO's vision of "digital transformation of agriculture" and supports the integration of nuclear techniques into broader frameworks of sustainable intensification (FAO/IAEA, 2018).

Ethical and Practical Considerations

As digital systems increasingly mediate agricultural knowledge, ethical and practical considerations arise. Data governance is essential: irradiation experiments involve not only physical parameters but also biological materials that may have intellectual property implications. Ontological repositories should therefore incorporate metadata on data ownership, licensing, and privacy. The use of open licenses, such as Creative Commons Attribution, ensures that ontological content remains accessible to researchers while protecting contributors' rights.

Training and accessibility are equally important. For many agronomists, the terminology of ontologies and artificial intelligence remains unfamiliar. Educational initiatives that translate these concepts into practical agricultural examples can encourage adoption. Ontologies like OnTop and OnSIR were designed with this pedagogical dimension in mind, using intuitive hierarchies and clear definitions rather than abstract formalism (ALVES et al., 2025; ALVES et al., 2026).

Finally, digital infrastructures must be aligned with physical capacity. Ontological reasoning and AI-based recommendations depend on the availability of well-calibrated irradiation facilities and accurate experimental data. For many developing countries, this implies investment not only in digital tools but also in physical laboratories and training programs. The synergy between technological infrastructure and human expertise is what will ultimately determine the success of digital radiation agronomy.

Future Perspectives

The convergence of nuclear techniques and digital agriculture heralds a new phase in the evolution of agronomic science. In the past, the emphasis was on discovering radiation effects experimentally; today, the challenge is to integrate, standardize, and predict them. Ontologies provide the language, while AI provides the logic. Together, they can enable predictive modeling of radiation outcomes, optimizing doses for each species and environment.

One promising direction is the creation of international ontological registries for plant radiobiology, analogous to genetic databases. Such registries would store dose–response curves, seed parameters, and environmental metadata in standardized formats, accessible to both scientists and policymakers. Combined with climate and soil datasets, they could inform large-scale strategies for sustainable intensification, using radiation as a safe and precise input technology.

The broader vision is that every radiation experiment conducted in agriculture contributes not only to local knowledge but also to a shared, evolving digital ecosystem. When described through ontological standards, even small studies gain global relevance. This democratization of data aligns with the open-science principles endorsed by FAO and UNESCO, ensuring that the benefits of radiation research reach all regions, including those most in need of resilient agricultural solutions.

In summary, digital and ontological approaches do not replace the traditional methods of radiation agronomy: they amplify them. They transform scattered results into structured, accessible and actionable knowledge.

Perspectives and Conclusions

Ionizing radiation continues to provide valuable tools for sustainable agriculture. From mutation breeding to physiological stimulation, its effects depend critically on dose, context and biological material. Future progress will hinge on the convergence between traditional experimentation and digital knowledge infrastructures. Standardized data, interoperable ontologies and intelligent reasoning systems can transform isolated findings into actionable insights. Through this integration, radiation agronomy may evolve from an empirical field into a predictive and data-driven science, aligning nuclear techniques with the broader goals of sustainable and intelligent agriculture.

Historical Reflection and Scientific Continuity

The trajectory of ionizing radiation in agriculture mirrors the broader evolution of agricultural science: it began as an experimental curiosity, matured into a set of standardized practices, and now moves toward data integration and intelligent decision support. During the 1950s and 1960s, the prevailing optimism surrounding nuclear energy fostered extensive experimentation with gamma irradiation in plant breeding, pest control and food preservation. This early period of nuclear agronomy, characterized by unbounded confidence in scientific progress, remains an enduring source of inspiration. Researchers such as Peter B. Vose, extensively cited throughout this chapter and with whom one of the authors had the opportunity to collaborate during his stay at the Center for Nuclear Energy in Agriculture, systematized the methodology and established a coherent theoretical foundation that demonstrated how radiation could serve as a controlled and reproducible variable in biological research. That pioneering period produced not only mutant varieties and improved post-harvest technologies but also a distinctive scientific ethos.

Today, that same ethos reemerges under different technological conditions. Where earlier researchers relied on analog dosimeters and field notebooks, modern scientists operate with automated irradiators, spectrophotometers and digital data loggers. The challenge, however, remains essentially the same: understanding how a physical process (the deposition of energy in matter) translates into a biological response that can be useful for agriculture. The continuity between past and present underscores the durability of radiation as an agricultural tool and the foresight of early nuclear agronomists who saw in it not a transient innovation but a permanent addition to the scientific toolkit.

The empirical knowledge accumulated during the twentieth century provides the empirical backbone for contemporary developments in radiohormesis and digital agronomy. The experimental design principles introduced by VOSE (1980) (control of seed moisture, calibration of source geometry, and replication under field conditions) remain valid today. What has changed is the capacity to measure, record and analyze these parameters at scales unimaginable to earlier generations. The rise of computational modeling and ontological representation brings to fruition the very ideal those pioneers anticipated: a precise and quantitative understanding of how radiation interacts with living systems.

From Empirical Observations to Predictive Models

Historically, the use of radiation in agriculture followed an empirical trajectory: researchers exposed plant material to a range of doses and observed the outcomes. The resulting dose–response curves were plotted manually and compared across experiments. While effective for identifying general trends, this approach could not easily capture the multitude of interacting variables (seed physiology, dose rate, oxygen concentration or genetic background) that shape the biological effect.

Contemporary data science changes this paradigm. By digitizing and semantically annotating experiments, scientists can construct predictive models that relate physical parameters to biological outcomes. For instance, integrating dose, dose rate and moisture content within an ontology allows statistical and machine-learning algorithms to identify patterns that would be invisible in narrative reports. Instead of stating that “10 Gy stimulated germination,” researchers can now compute probabilistic thresholds: under defined conditions, a given dose has a quantifiable likelihood of producing stimulation rather than inhibition.

Such predictive capability has practical importance. In mutation breeding, it enables more efficient determination of LD_{50} values without extensive preliminary trials. In radiohormetic seed priming, it allows optimization of treatment protocols for specific cultivars. And in phytosanitary irradiation, predictive models can balance microbial inactivation with organoleptic characteristics preservation. The transition from empirical observation to predictive analytics thus represents a natural continuation of the discipline’s maturation.

Reproducibility, Standardization and the Role of Ontologies

A persistent challenge in radiation agronomy has been the difficulty of reproducing results across laboratories. Slight variations in seed storage, humidity or dose measurement can shift outcomes dramatically. The introduction of ontologies addresses this problem by enforcing standardized descriptors for all relevant parameters. When experiments are annotated using shared concepts (*hasMoistureContent*, *hasDoseRate*, *usesSourceType*, *hasObservedOutcome*) their metadata become interoperable, allowing results from different regions to be compared directly.

The OnSIR ontology exemplifies this principle. It formalizes key entities, each defined by quantitative and qualitative attributes. By assigning persistent identifiers to these concepts, OnSIR ensures that the term “low dose” means the same thing in every dataset. Similarly, the OnTop ontology standardizes agronomic contexts (soil condition, management action, or yield outcome) enabling cross-domain integration. Together, these ontologies create a shared language for describing radiation experiments in agriculture, bridging the gap between physical measurement and biological interpretation (ALVES et al., 2025; ALVES et al., 2026).

Reproducibility is not merely a methodological virtue, it is a prerequisite for practical application. Farmers and seed companies will only adopt irradiation-based technologies if their effects are consistent and predictable. Standardized data models provide the foundation for this reliability.

Integration into Sustainable Agricultural Systems

Radiation technology aligns with many of the objectives of sustainable agriculture. It reduces chemical inputs, extends food shelf life and enhances genetic diversity without transgenic modification. When applied responsibly, it leaves no residues and consumes minimal energy. Yet the sustainable implementation of radiation requires coordination among physical facilities, agronomic institutions and regulatory frameworks.

In seed technology, low-dose irradiation offers a clean alternative to chemical seed treatments. Instead of fungicides or growth regulators, a short exposure to gamma rays can achieve similar effects in terms of vigor and germination speed. In post-harvest management, irradiation reduces food waste (a critical aspect of sustainability) by preventing spoilage and extending shelf life. The FAO and IAEA continue to support the establishment of irradiation facilities in developing countries, recognizing their potential to strengthen food security and reduce post-harvest losses (FAO/IAEA, 2018).

Sustainability also involves knowledge sustainability: the ability to preserve and transmit scientific information across generations. Ontological frameworks contribute to this dimension by making radiation data findable, accessible, interoperable and reusable (the FAIR principles). A radiation experiment conducted today, if properly annotated, could remain interpretable decades later, regardless of personnel changes or software evolution. This continuity ensures that the cumulative investment in nuclear agricultural research continues to yield benefits.

Interdisciplinary Synergy: Physics, Biology and Computer Science

Radiation agronomy exemplifies the interdisciplinary nature of modern agricultural research. It brings together the precision of physics, the complexity of biology and the interpretive power of data science. Each discipline contributes essential insights: physics provides the quantitative framework for energy deposition, biology reveals the pathways of stress and adaptation, informatics integrates both into predictive systems.

The success of this interdisciplinary approach depends on mutual literacy among disciplines. Physicists must understand the biological relevance of dose, while agronomists must appreciate the constraints of dosimetry and safety. Data scientists, in turn, must translate biological complexity into structured models without oversimplification. Training programs and collaborative projects are therefore vital. Universities and international agencies could develop multidisciplinary curricula that combine nuclear science, plant physiology and information management, preparing a new generation of “digital nuclear agronomists.”

Public Perception, Safety, and Communication

Despite decades of safe use, public perception of radiation in agriculture remains ambivalent. Misunderstanding arises mainly from the conflation of irradiation (by energy exposure) with radioactivity (by nuclear contamination). Educational outreach must therefore emphasize that irradiated seeds or foods do not become radioactive; they merely absorb a controlled amount of energy that modifies biological processes without leaving residual radioisotopes (VOSE, 1980).

Public communication should highlight the comparative safety and environmental benefits of irradiation relative to chemical or thermal alternatives. In phytosanitary control, for instance, irradiation replaces fumigants that deplete the ozone layer. In food preservation, it avoids chemical preservatives that may pose health concerns. Moreover, unlike genetic modification, mutation breeding via irradiation relies on natural repair mechanisms and does not introduce foreign DNA. Transparency in labeling and certification, supported by international standards, can further enhance consumer confidence.

Digital technologies can assist in communication by providing accessible, ontology-based information outlets. Farmers and consumers could query these systems for explanations of terms like “gamma treatment,” “low dose,” or “hormetic effect,” receiving scientifically validated but non-technical descriptions. In this way, digital infrastructure not only serves researchers but also becomes a tool for science education and public trust.

Economic and Institutional Dimensions

The economic viability of radiation applications depends on cost efficiency, infrastructure and institutional support. Establishing and maintaining irradiation facilities requires significant investment, but the long-term returns can be substantial when facilities are shared across multiple sectors (agriculture, food industry and medical sterilization). Regional centers of excellence, coordinated by agencies like the IAEA, can provide services to surrounding countries, optimizing utilization and reducing costs.

At the institutional level, the integration of nuclear and digital agriculture demands coherent governance. Regulations must ensure safety without creating unnecessary barriers to innovation. Harmonized licensing procedures, common dosimetry standards and mutual recognition of certifications would facilitate international trade of irradiated seeds and products. Moreover, policies encouraging open data and ontology-based reporting can enhance transparency and collaboration. Through the Atoms4Food initiative, the FAO and IAEA are exploring digital and irradiation-based approaches for sustainable agrifood systems (IAEA, 2023).

Scientific Frontiers: Low-Dose Mechanisms and Systems Biology

From a scientific perspective, the frontier lies in elucidating the mechanisms of low-dose effects. While the biphasic dose–response pattern is well established empirically, its molecular underpinnings remain incompletely understood. Advances in systems biology, particularly omics technologies, provide new opportunities to explore these mechanisms at multiple levels.

Integrating omics data with radiation parameters could reveal how specific pathways respond to low-dose exposure. For example, transcriptomic analysis might identify genes involved in oxidative stress response, DNA repair or hormone signaling that are transiently upregulated after irradiation. Metabolomics could detect shifts in primary metabolites indicating enhanced energy metabolism. When mapped within an ontological framework, these molecular responses can be linked to macroscopic traits such as germination speed or biomass accumulation, completing the chain from physics to phenotype.

Regional Opportunities and Global Cooperation

Developing countries stand to gain disproportionately from advances in radiation agronomy. Many already possess basic irradiation infrastructure for medical or industrial use, which can be adapted for agricultural applications. Low-dose seed priming could help overcome germination challenges in arid or saline environments, while mutation breeding could generate locally adapted varieties without the high cost of genetic engineering. Furthermore, food irradiation can reduce post-harvest losses in tropical climates, contributing directly to food security.

Global cooperation, facilitated by FAO/IAEA programs, plays a pivotal role. Shared ontological frameworks and open data platforms ensure that results from one country inform practices in another. A study on hormesis in tobacco conducted in Brazil, for example, can be compared with data on groundnut or maize from Africa or Asia, using standardized descriptors. Such interoperability fosters equitable scientific participation, ensuring that innovations are not confined to a few technologically advanced nations.

3 VISION FOR THE NEXT DECADES

Looking ahead, the integration of nuclear and digital technologies promises to change the landscape of agricultural research. The coming decades are likely to witness the emergence of three interrelated trends:

1. Predictive Radiation Agronomy.

Combining empirical data with ontological modeling and machine learning will allow the prediction of radiation outcomes under specific environmental and biological conditions. Researchers will be able to input parameters such as dose, moisture and seed variety and obtain probabilistic forecasts of germination, growth, or mutation frequency. Such predictive tools will save resources, reduce experimental redundancy and enhance precision.

2. Autonomous Irradiation Systems.

Automation and robotics could enable fully controlled seed treatment facilities where dosimetry, exposure and post-irradiation handling are regulated by digital feedback loops. Sensors measuring temperature, humidity and seed moisture would adjust irradiation parameters in real time, maintaining optimal conditions for desired effects. Data from each batch would be automatically uploaded to a centralized ontology-based database, ensuring traceability.

3. Integrated Decision Support Platforms.

Digital agriculture platforms that currently manage irrigation, fertilization and pest control will eventually incorporate radiation modules. These modules will advise on whether irradiation should be applied, at what dose and in which growth stage. The recommendations will draw upon accumulated ontological data, environmental monitoring and predictive models. Farmers could access such systems via mobile applications, bringing the benefits of nuclear science directly to the field.

Concluding Remarks

The history of ionizing radiation in agriculture is a story of transformation: from experimental curiosity to established practice, from empirical observation to predictive modeling, from isolated results to interoperable knowledge. Each phase built upon the previous one, expanding not only technical capacity but also conceptual depth.

Today, as agriculture faces unprecedented challenges (polution, soil degradation and food insecurity in times of abundance) the insights of radiation agronomy acquire renewed significance. The same physical principles that once yielded mutant varieties and preserved foods can now contribute to precision farming, stress tolerance and data-driven sustainability.

By merging the rigor of nuclear physics with the adaptability of biological systems and the connectivity of digital technologies, the field offers a model for scientific integration.

In practical terms, this integration demands three commitments. First, to maintain experimental excellence. Second, to ensure data interoperability through standardized ontologies and open repositories. Third, to communicate transparently with the public, reaffirming the safety and benefits of nuclear techniques. These commitments will ensure that radiation remains a trusted and innovative component of agricultural science.

Ultimately, the future of radiation agronomy will depend not on isolated breakthroughs but on cumulative, collaborative progress. Each experiment, each dataset and each ontology contributes to a global mosaic of knowledge. The synergy of physics, biology, agronomy and digital intelligence could illuminate the pathways of plant life with unprecedented clarity.

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ANALYSIS OF SCC AND SPC INDICES IN MILK TANKS AND THEIR CORRELATION WITH GOOD PRACTICES IN DAIRY CATTLE FARMING

ANÁLISE DOS ÍNDICES DE CCS E CPP EM TANQUES DE LEITE E SUA CORRELAÇÃO COM AS BOAS PRÁTICAS NA BOVINOCULTURA LEITEIRA

ANÁLISIS DE LOS ÍNDICES DE CCS Y CPP EN TANQUES DE LECHE Y SU CORRELACIÓN CON LAS BUENAS PRÁCTICAS EN LA GANADERÍA LECHERA

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ABSTRACT
The present study aimed to evaluate the influence of adopting Good Milking Practices (GMP) on milk quality parameters, specifically the Standard Plate Count (SPC) and Somatic Cell Count (SCC), in rural properties of the Montes Claros (MG) microregion. This is a descriptive, documentary, retrospective, and quantitative research conducted in October 2023, with a sample of six farms from the local dairy basin. Data were analyzed through Tables and tables created using Excel software. The results indicated that property P2, which showed the highest adherence to GMP, obtained the lowest SCC (264,000 somatic cells/mL) and SPC (21,000 CFU/mL) values, reflecting better hygienic-sanitary milk quality. In contrast, property

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P3, with lower adherence to the recommended practices, presented the highest SCC (1,170,000 somatic cells/mL) and SPC (23,000 CFU/mL) indices, indicating milk of lower quality. It is concluded that the proper implementation of Good Agricultural Practices has a direct positive influence on reducing SCC and SPC indices, promoting the production of milk with higher microbiological and hygienic-sanitary quality, thus contributing to food safety and enhancing the product's market value.

Keywords: Good Agricultural Practices. Hygienic-Sanitary Milk Quality. Food Safety.

RESUMO
O presente estudo teve como objetivo avaliar a influência da adoção de Boas Práticas de Ordenha (BPO) sobre os parâmetros de qualidade do leite, especificamente a contagem padrão em placas (CPP) e a contagem de células somáticas (CCS), em propriedades rurais da microrregião de Montes Claros (MG). Trata-se de uma pesquisa descritiva, documental, retrospectiva e quantitativa, realizada em outubro de 2023, com uma amostra de seis propriedades da bacia leiteira local. Os dados foram analisados por meio de gráficos e tabelas elaborados no software Excel. Os resultados indicaram que a propriedade P2, que apresentou maior adesão às BPO, obteve os menores valores de CCS (264.000 células somáticas/mL) e CPP (21.000 UFC/mL), refletindo melhor qualidade higiênico-sanitária do leite. Em contrapartida, a propriedade P3, com menor adesão às práticas recomendadas, apresentou os maiores índices de CCS (1.170.000 células somáticas/mL) e CPP (23.000 UFC/mL), indicando leite de menor qualidade. Conclui-se que a implementação adequada das boas práticas agropecuárias tem influência positiva direta na redução dos índices de CCS e CPP, promovendo a produção de leite com maior qualidade microbiológica e higiênico-sanitária, contribuindo para a segurança alimentar e valorização do produto no mercado.

Palavras-chave: Boas Práticas Agropecuárias. Qualidade Higiênico-Sanitária do Leite. Segurança Alimentar.

RESUMEN
El presente estudio tuvo como objetivo evaluar la influencia de la adopción de Buenas Prácticas de Ordeño (BPO) sobre los parámetros de calidad de la leche, específicamente la Recuento en Placa Estándar (RPE) y la Recuento de Células Somáticas (RCS), en propiedades rurales de la microrregión de Montes Claros (MG). Se trata de una investigación descriptiva, documental, retrospectiva y cuantitativa, realizada en octubre de 2023, con una muestra de seis propiedades de la cuenca lechera local. Los datos fueron analizados mediante gráficos y tablas elaborados en el software Excel. Los resultados indicaron que la propiedad P2, que presentó mayor adhesión a las BPO, obtuvo los valores más bajos de RCS (264.000 células somáticas/mL) y RPE (21.000 UFC/mL), reflejando una mejor calidad higiénico-sanitaria de la leche. En cambio, la propiedad P3, con menor adhesión a las prácticas recomendadas, presentó los índices más altos de RCS (1.170.000 células somáticas/mL) y RPE (23.000 UFC/mL), indicando leche de menor calidad. Se concluye que la implementación adecuada de las Buenas Prácticas Agropecuarias tiene una influencia positiva directa en la reducción de los índices de RCS y RPE, promoviendo la producción de leche con mayor calidad microbiológica e higiénico-sanitaria, contribuyendo a la seguridad alimentaria y a la valorización del producto en el mercado.

Palabras clave: Buenas Prácticas Agropecuarias. Calidad Higiénico-Sanitaria de la Leche. Seguridad Alimentaria.

1 INTRODUCTION

The milk production chain is one of the most relevant segments of Brazilian agribusiness, playing a strategic role in generating employment and income, both directly and indirectly, in several municipalities in the country (Rocha; Oak; Resende, 2020). In 2019, the gross value of primary milk production reached R$ 35 billion, positioning it as the seventh most economically important agricultural product in Brazil (Brasil, 2020). In this scenario of significant economic relevance, there is also an increase in global demand for products of animal origin and the continuous growth in the consumption of milk and dairy products.

This movement, combined with society's growing concerns about environmental and animal welfare issues, imposes on dairy farms the need to improve their production systems. To meet these requirements, it is essential to increase productivity in line with the preservation of the health and well-being of herds, as well as the mitigation of environmental impacts. Such a context demands high levels of efficiency in production processes, ensuring the sustainability and competitiveness of the sector (Bahlo *et al*., 2019; Bianchi *et al*., 2022).

The quality of milk is defined by a set of physicochemical and microbiological parameters that determine its composition, safety and technological aptitude. The physicochemical evaluation includes the quantification of total protein, casein, fat, lactose, total solids (TS), non-fat solids (NGS), free fatty acids (FFA) and citric acid content, in addition to measurements of pH, freezing point (FPD), density and titratable acidity (Turner scale), which are fundamental to estimate the suitability of milk for the production of derivatives such as curd (Calahorrano-Moreno *et al*., 2022).

At the microbiological level, the somatic cell count (SCC) is used as an indicator of mammary gland health and management hygiene, while different chemical contaminants and pathogens, such as Escherichia coli, Staphylococcus aureus and Streptococcus uberis, are associated with milk spoilage and reduced shelf life. These changes compromise the sensory and technological characteristics of the product, generating economic losses and reducing the final quality in the industry (Zalewska *et al*., 2025).

Considering the multiple routes of contamination, both direct and indirect, bovine milk can present different contaminants of a chemical and microbiological nature (Calahorrano-Moreno *et al*., 2022). In order for the product to meet the quality standards established by Brazilian legislation, the somatic cell count (SCC) must be equal to or less than 500,000 cells/mL, while the standard plate count (CPP) — an indicator of the population of viable bacteria per milliliter — must not exceed 300,000 CFU/mL, the latter being related to both intramammary infections and environmental sources and fomites in contact with milk (Brazil, 2018).

Under ideal conditions, freshly milked milk from healthy cows has a low total bacterial count (<10^3 CFU/mL); however, these values can rise rapidly when the product is kept at room temperature. Immediate storage in sanitized containers and refrigerated at 4 °C slows microbial growth until pasteurization is carried out in processing units (Rinaldi *et al*., 2010; Cheng and Han, 2020). Therefore, the implementation of good hygiene practices in milking, associated with sanitary, nutritional and environmental management, is essential to keep the initial microbial load of milk low. The cleaning of equipment and teats, combined with disease control, reduces SSC and SCC, preventing changes in the composition of the product. The provision of a balanced diet and thermal comfort minimize animal stress and favor the health of the mammary gland. Adequate environmental conditions and waste management complement the prevention of contamination (Mogotu *et al*., 2022).In addition, the adoption of good management and hygiene practices in dairy production contributes to the significant reduction of SCC and CPP, directly impacting the quality and safety of the final product. The improvement of these parameters is reflected in the greater acceptance of milk in the market, in compliance with legal requirements and in the valorization of the raw material, favoring the competitiveness of the sector (Carneiro; Shah; Ribeiro, 2023).

In summary, the present study aimed to evaluate the influence of the adoption of Good Milking Practices on the Standard Plate Count (SSC) and the Somatic Cell Count (SCC) in dairy farms located in the microregion of Montes Claros, aiming to establish the relationship between hygienic-sanitary practices and the quality indicators of the milk produced.

2 MATERIALS AND METHODS

The research characterized as descriptive, involves the collection and analysis of data regarding Good Agricultural Practices (GAP) and milk quality indexes in rural properties. The purpose was to describe the relationship and evaluate the reciprocal influence between the adoption of BPAs and milk quality within the study period. The theoretical foundations for the analysis of the theme were based on the works of Rocha (2020), Linhares, Landin and Ribeiro (2021), Anésio and Dornelas (2020).

Data collection was carried out in October 2023, in six dairy farms located in the municipalities of Montes Claros, Bocaiúva and Francisco Sá, which are part of the dairy basin in the North of Minas Gerais. The selected properties supplied milk to the same dairy and were chosen based on the profile of suppliers in the industry, considering criteria such as availability of producers, authorization of access to the facilities, presence of individual cooling tank and logistical feasibility for transporting the samples.

In each property, the information was obtained through direct observations and analysis of records provided by the responsible Veterinarian, including zootechnical indices and animal management. These data supported the completion of a checklist prepared by the researchers, consisting of 19 items related to the conditions of the milking equipment, management during milking and hygiene procedures. Each topic was classified as "yes" when the practice was adopted or "no" when non-existent, allowing the level of compliance with Good Agricultural Practices (GAP) to be identified.

In collaboration with the cooperative responsible for milk collection, the results of laboratory analyses were obtained regarding milk quality, represented by the indicators of tank count (SCC) and (CPP), calculated from the geometric means of the collections carried out in the reference month.

The research, of a documentary nature and quantitative approach, was based on data provided by the Veterinarian and the cooperative, considering only the execution of the practices. Then, the information regarding the management and milking routine were organized, together with the results of SCC and CPP, in electronic spreadsheets (Microsoft Excel®), which allowed the comparative analysis and the quantitative description of the indicators between the farms.

3 RESULTS AND DISCUSSION

In this study, six milk supplier properties that presented samples in non-compliance with the counting parameters of (CCS) and (CPP) were visited, together with the Veterinarian in charge. The visits took place in October 2023, with the collection of information for analysis of the adoption of Good Agricultural Practices (GAP). The evaluation was carried out using checklist spreadsheets, and the results were compiled and presented graphically, allowing the subsequent comparison of the values of SSC and SCC of the tank milk. In the properties evaluated, there was a wide variation in the results obtained, especially in the SCC values, which suggests problems related to the health of the herd. As shown in Table 1, only the P2 farm presented SCC values below the limit established by Normative Instruction No. 76, while all the others presented averages above the maximum allowed value (500,000 cells/mL).

Regarding the results of (CBT), all properties presented values within the limits established by Normative Instruction No. 76, with geometric means below 75,000 CFU/mL, as shown in Table 1. The maximum value allowed by this regulation is 300,000 CFU/mL, evidencing compliance with the results obtained.

Table 1

Geometric mean values of Somatic Cell Count (SCC) and Standard Plate Count (SSC) of tank milk from six dairy farms located in the north of Minas Gerais

Milk quality indicators	Rural Properties					
	P1	**P2**	**P3**	**P4**	**P5**	**P6**
CCS (cells/mL)	702.000	264.000	1.170.000	619.000	551.000	916.000
CPP	25.000	21.000	23.000	66.000	74.000	51.000

Source: The authors (2025).

The evaluation of the conditions of the equipment (Table 2) showed that, of the six properties analyzed, four presented milking systems in good condition. However, none of them had a record of specialized maintenance of this equipment in the six months prior to the survey. Regarding the cooling tank, only the properties P5 and P6 had been maintained in the period evaluated. The absence of adequate preventive and corrective maintenance directly compromises the microbiological and physicochemical quality of milk, contributing to increases in the values of Somatic Cell Count (SCC) and Standard Plate Count (CPP). These parameters, when high, increase the risk of occurrence of acidic milk and antibiotic residues, which compromises its compliance with legal quality standards. The adoption of appropriate management practices, in line with milk quality standards, favors not only the improvement of the quality of the final product, but also the increase in productivity and profitability of the dairy activity (Anésio; Dornelas, 2020).

Table 2

Operational conditions of milking equipment in six dairy farms located in the north of Minas Gerais

Checklist for Analysis of Milking Equipment Conditions	Rural Properties					
	P1	P2	P3	P4	P5	P6

Is the milking equipment in good condition?	NO	YES	YES	YES	YES	NO
Is the maintenance of the milking equipment up to date? (made in the last 6 months)	NO	NO	NO	NO	NO	NO
Is cooling tank maintenance up to date? (made in the last 6 months)	NO	NO	NO	NO	YES	YES

Source: The authors (2025).

The analysis of milking management (Table 3) revealed that five of the six farms did not meet at least one of the nine parameters evaluated. However, all establishments correctly performed the mug test, pre-dipping, over-milking and post-dipping, in addition to including the management of calf feedings immediately after milking, indicating adherence to the basic practices essential to the procedure. Regarding over-milking, the properties P2, P4 and P5 did not present this stage, and were also those with the lowest mean SCC, which suggests that the absence of this practice can negatively impact breast health and increase the somatic cell count. Additionally, the compliance with the milking line and with the zootechnical records revealed non-conformities only in P4. Regarding the recording of cases of clinical mastitis, only P2 and P5 maintained this control, which is important for epidemiological monitoring and decision-making. Barbosa, Costa and Bombonato (2022), when evaluating five farms in the Alto Paranaíba region (MG), identified critical failures in milking practices such as absence of pre- and post-dipping, inadequate cleaning of teats and lack of equipment maintenance as factors directly related to the increase in the prevalence of mastitis and SCC. The adoption of Good Milking Practices (BPO), combined with staff training and equipment maintenance and calibration, led to a significant reduction in mastitis in the analyzed properties.

Table 3

Evaluation of milking management parameters in six dairy farms located in the north of Minas Gerais

Checklist for milking management evaluation.	**Rural Properties**					
	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Is the mug test performed on all milkings?	YES	YES	YES	YES	YES	YES
It is performed pre-dipping	YES	YES	YES	YES	YES	YES

Is the pre-dipping drying?	YES	YES	YES	YES	YES	YES
Is milking removed before cows are overmilked?	NO	YES	NO	YES	YES	NO
Is post-dipping carried out, or are the cows placed with the cows immediately after milking?	YES	YES	YES	YES	YES	YES
Are cows managed calmly without stress ?	NO	YES	NO	YES	NO	YES
Do you perform milking line?	YES	YES	YES	NO	YES	YES
Do you make zootechnical notes of the animals?	YES	YES	YES	NO	YES	YES
Do you take notes and control cases of clinical mastitis?	NO	YES	NO	NO	YES	NO

Source: The authors (2025).

The evaluation of the hygiene practices of the milking equipment indicated that five of the six properties fully complied with the recommended protocols, according to the checklist adopted in the research. Only the P6 farm presented a non-conformity, related to the absence of the pre-rinsing step recommended as the first phase of immediate cleaning after milking. This step is essential for the removal of milk residues not conducted to the cooling tank, avoiding the formation of biofilms and facilitating the action of subsequent detergents and sanitizers. By relating the diagnosis of the hygienic-sanitary conditions of the animals and the milking equipment with the results of SCC and SSC (Table 1), it was observed that, although the P6 farm had a satisfactory performance in the parameters related to the conditions of the animals and the organization of the milking line, it presented high values of SCC and SSC in the milk of the tank. This result may be associated with deficiencies in the milkers' personal hygiene procedures, an aspect that was not evaluated in this study. Similar results were described by Linhares, Landin, and Ribeiro (2021), who, when analyzing two properties in the municipality of Bom Jardim de Minas (MG), found that the P1 property, even correctly following the pre-dipping and post-dipping practices, had high SCC. The authors suggest that, in these cases, the cause may be related to the difficulty in diagnosing and controlling subclinical mastitis, reinforcing the need for complementary health monitoring strategies.

Table 4

Characterization of the procedures for cleaning milking equipment in six dairy farms located in the north of Minas Gerais

Checklist for Milking Equipment Cleanliness Assessment	Rural Properties					
	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Are liners disinfected between milkings?	YES	YES	YES	YES	YES	YES
Pre-rinse is performed	YES	YES	YES	YES	YES	NO
Hot water cycle with detergent	YES	YES	YES	YES	YES	YES
Physical removal of waste	YES	YES	YES	YES	YES	YES
Acid rinse	YES	YES	YES	YES	YES	YES
Equipment and utensils are cleaned and sanitized	YES	YES	YES	YES	YES	YES
Is there a person responsible for monitoring the hygiene of utensils and equipment?	YES	YES	YES	YES	YES	YES

Source: The authors (2025).

According to Nascimento *et al*. (2021), sanitization carried out with the use of disinfectants reduces the burden of pathogens to levels considered safe. In this context, the producers' technical knowledge about the hygiene procedures of the milking equipment is decisive to ensure the quality of the milk throughout the production stages and based on armazenamento.Com checklist tables presented, the data obtained were integrated, aiming to correlate the main indicators of raw material quality with the number of items served in each property. This analysis allowed us to identify which parameters exerted the greatest influence on the maintenance of low values of these indicators, as shown in Table 5.

Table 5

Evaluation of the microbiological quality and somatic cell count (SCC) of tank milk according to the management practices identified in the checklists applied

Number of practices analyzed performed in each checklist	Rural Properties					
	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Conditions of milking equipment	0	1	1	1	2	1
Evaluation of milking management	6	9	6	6	8	7

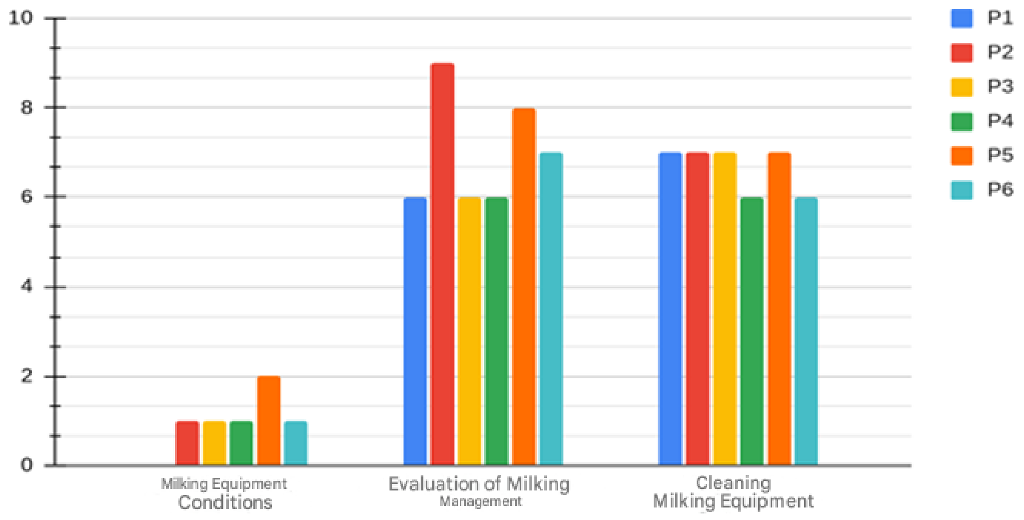
Milking Equipment Cleaning	7	7	7	6	7	6
Total Quantity	13	17	14	13	17	14

Source: The authors (2025).

The data presented in Table 5 were graphically organized in Figure 1, allowing a better visualization and comparison of the performance of each property in terms of the practices adopted.

Figure 1

Comparison of good agricultural practices observed and evaluated through checklists on each property



Source: The authors (2025).

It is observed that the rural property P2 (represented in red) presented the highest sum of good agricultural practices (GAP), reflected in the lowest values of count (SCC), with 264,000 somatic cells/mL, and (CPP), with 21,000 CFU/mL. These results indicate a higher quality of the milk produced. In contrast, the P3 (yellow) property obtained the highest levels of SCC (1,170,000 somatic cells/mL) and CPP (23,000 CFU/mL), showing the lowest milk quality among those evaluated. Thus, as shown in Table 1, the classification of the farms in ascending order of SCC parameter associated with herd health was: P2, P4, P5, P1, P6 and P3. In relation to the SSC indicator of hygiene during milking and management, the order was: P2, P3, P1, P6, P4 and P5. According to Linhares, Landin, and Ribeiro (2021), the joint analysis of CCS and CPP, combined with the application of checklists, allows the identification of flaws in the processes of obtaining milk, facilitating the implementation of corrective measures. However, the effectiveness of these actions depends directly on the commitment of rural producers to modify inappropriate practices and invest in technologies, products and equipment that ensure higher milk quality.

4 CONCLUSION

Farms that correctly adopted BPAs presented, in most cases, lower SCC and CPP, indicating better milk quality and contributing to food safety and public health. The quality of milk impacts the entire production chain, benefiting producers, industry and consumers. Products with better hygienic-sanitary standards generate greater confidence in the market and increase the competitiveness of the dairy sector, especially in the face of quality bonus policies. Some farms that adopted management practices still had high SCC rates, which may be related to the low effectiveness in the execution of the practices, an aspect not analyzed in this study. Factors such as the quality of milking cleanliness can be addressed in future research.

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THE MUCILAGE OF FORAGE CACTUS: A SUSTAINABLE ALTERNATIVE FOR FOOD PRESERVATION AND BIODEGRADABLE PACKAGING

A MUCILAGEM DA PALMA FORRAGEIRA: UMA ALTERNATIVA SUSTENTÁVEL PARA A CONSERVAÇÃO DE ALIMENTOS E EMBALAGENS BIODEGRADÁVEIS

LA MUCILAGO DE LA PALMA FORRAJERA: UNA ALTERNATIVA SOSTENIBLE PARA LA CONSERVACIÓN DE ALIMENTOS Y ENVASES BIODEGRADABLES

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ABSTRACT
The forage cactus (*Opuntia spp.)* stands out as a strategic crop for semiarid regions due to its high water-use efficiency and resistance to water stress and intense solar radiation. In addition to its fundamental role in animal feeding, this species shows great potential for the utilization of bioactive compounds with industrial applications. Among these compounds, the mucilage extracted from the cladodes has attracted increasing scientific and technological interest. It is a natural, biodegradable, and biocompatible polysaccharide, whose physicochemical properties provide it with high water retention capacity, viscosity, and the ability to form films and gels. These characteristics make cactus mucilage a promising alternative for the production of biodegradable packaging and edible coatings, especially in the post-harvest preservation of fruits and vegetables, contributing to loss reduction and extended shelf life. Beyond reducing dependence on synthetic polymers, its use adds value to the cactus crop and promotes the development of the regional bioeconomy, with a positive impact on environmental sustainability and food security. However, the advancement of its large-scale application depends on further studies aimed at standardizing extraction methods, chemically characterizing the compound under different edaphoclimatic conditions, and evaluating its performance in cultivation systems. Thus, the full utilization of forage cactus, especially its mucilage, represents a concrete opportunity for technological innovation and the valorization of natural resources adapted to semiarid environments.

Keywords: Sustainability. Natural Polysaccharides. Post-Harvest Preservation.

RESUMO
A palma forrageira (*Opuntia spp*.) destaca-se como uma cultura estratégica para as regiões semiáridas, em razão de sua elevada eficiência no uso da água e resistência a condições de estresse hídrico e alta radiação solar. Além de seu papel fundamental na alimentação animal, essa espécie apresenta grande potencial para o aproveitamento de compostos bioativos com aplicações industriais. Entre esses compostos, a mucilagem extraída dos cladódios tem despertado crescente interesse científico e tecnológico. Trata-se de um polissacarídeo natural, biodegradável e biocompatível, com propriedades físico-químicas que lhe conferem alta capacidade de retenção de água, viscosidade e formação de filmes e géis. Essas características tornam a mucilagem de palma uma alternativa promissora para a produção de embalagens biodegradáveis e revestimentos comestíveis, especialmente na conservação pós-colheita de frutas e hortaliças, contribuindo para a redução de perdas e o prolongamento da vida útil dos alimentos. Além de reduzir a dependência de polímeros sintéticos, seu uso agrega valor à cultura da palma e promove o desenvolvimento da bioeconomia regional, com impacto positivo na sustentabilidade ambiental e na segurança alimentar. Contudo, o avanço de sua aplicação em escala industrial depende de estudos adicionais voltados à padronização dos métodos de extração, à caracterização química sob diferentes condições edafoclimáticas e à avaliação de desempenho em sistemas cultivos. Assim, o aproveitamento integral da palma forrageira, especialmente da mucilagem, representa uma oportunidade concreta de inovação tecnológica e valorização de recursos naturais adaptados ao semiárido

Palavras-chave: Sustentabilidade. Polissacarídeos Naturais. Conservação Pós-Colheita.

RESUMEN
La palma forrajera (*Opuntia spp.)* se destaca como un cultivo estratégico para las regiones semiáridas debido a su alta eficiencia en el uso del agua y su resistencia a condiciones de

estrés hídrico y alta radiación solar. Además de su papel fundamental en la alimentación animal, esta especie presenta un gran potencial para el aprovechamiento de compuestos bioactivos con aplicaciones industriales. Entre estos compuestos, la mucilago extraída de los cladodios ha despertado un creciente interés científico y tecnológico. Se trata de un polisacárido natural, biodegradable y biocompatible, cuyas propiedades fisicoquímicas le confieren una alta capacidad de retención de agua, viscosidad y formación de películas y geles. Estas características hacen de la mucilago de palma una alternativa prometedora para la producción de envases biodegradables y recubrimientos comestibles, especialmente en la conservación poscosecha de frutas y hortalizas, contribuyendo a la reducción de pérdidas y a la prolongación de la vida útil de los alimentos. Además de reducir la dependencia de polímeros sintéticos, su uso agrega valor al cultivo de la palma y promueve el desarrollo de la bioeconomía regional, con un impacto positivo en la sostenibilidad ambiental y la seguridad alimentaria. Sin embargo, el avance de su aplicación a escala industrial depende de estudios adicionales orientados a la estandarización de los métodos de extracción, a la caracterización química bajo diferentes condiciones edafoclimáticas y a la evaluación del desempeño en sistemas de cultivo. Así, el aprovechamiento integral de la palma forrajera, especialmente de su mucilago, representa una oportunidad concreta de innovación tecnológica y valorización de los recursos naturales adaptados al semiárido.

Palabras clave: Sostenibilidad. Polisacáridos Naturales. Conservación Poscosecha.

1 INTRODUCTION

The growing demand for sustainable alternatives to synthetic materials has driven interest in natural compounds from plant sources, especially those capable of acting as biopolymers for industrial and food applications. In this context, the forage palm (*Opuntia* spp.), belonging to the *Cactaceae* family, stands out as a species of high biotechnological potential, widely cultivated in arid and semi-arid regions due to its extraordinary ability to adapt to conditions of water and thermal stress (QUEIROZ et al., 2015; PEREIRA et al., 2015). Originally from Mexico and introduced in Brazil at the end of the nineteenth century, the forage palm culture has consolidated itself as one of the main food alternatives for herds during long periods of drought, occupying a strategic position in livestock in the semi-arid northeast (PEREIRA et al., 2015).

Their wide adaptation to adverse edaphoclimatic conditions is associated with morphophysiological characteristics typical of plants with crassulaceous acid metabolism (CAM), which give them efficiency in water use and water storage capacity in the cladodes. Daytime stomatal closure and nocturnal CO_2 fixation significantly reduce transpiration losses, allowing the plant to maintain metabolic activity under severe water limitation (LÜTTGE, 2004, 2010). In addition, the superficial and extensively branched root system allows rapid absorption of moisture from sporadic rains or dew (SNYMAN, 2006). These adaptations make forage palm not only essential to the sustainability of regional livestock, but also an important source of biomass for industrial purposes.

Among the various bioactive components of this species, the mucilage extracted from cladodes has been gaining scientific and technological prominence. It is a high molecular weight heteropolysaccharide, consisting mainly of sugars such as arabinose, galactose and xylose (TRACHTENBERG; MAYER, 1981), with rheological and emulsifying properties that qualify it as a potential natural hydrocolloid (SÁENZ; SEPÚLVEDA; MATSUHIRO, 2004). Its biocompatibility, biodegradability, and ability to form films and gels make it promising for the formulation of coatings and edible films, applicable in food preservation and in the replacement of synthetic polymers derived from petroleum (GHERIBI et al., 2018).

In recent years, research has demonstrated the potential of forage palm mucilage in the postharvest preservation of fruits and vegetables, acting to reduce mass loss, maintain firmness and conservation of bioactive compounds (DEL-VALLE et al., 2005; ALLEGRA et al., 2016; MORAIS et al., 2019). In addition, its application in plasticized formulations increases its mechanical strength and flexibility, enabling its use in the manufacture of biodegradable packaging with performance comparable to conventional synthetic materials.

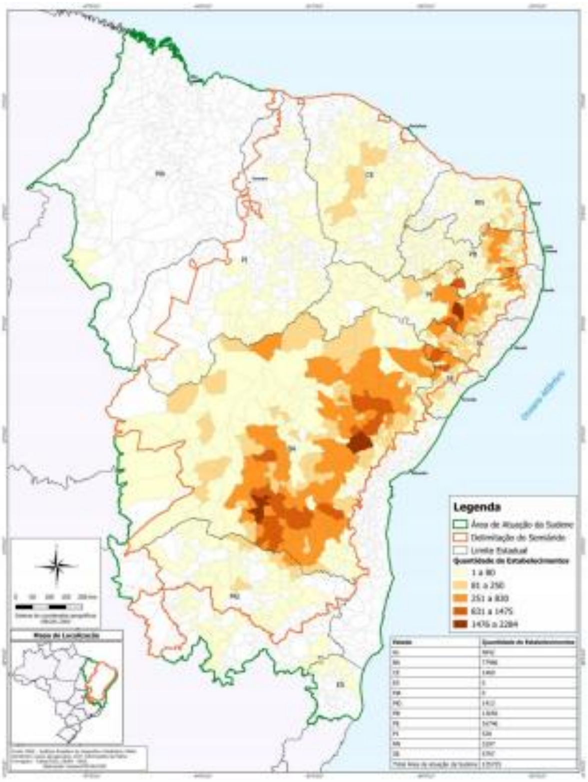
Thus, understanding the agronomic, structural and physicochemical aspects of forage palm and its mucilage is essential for the advancement of sustainable technologies aimed at the food and materials industry. Thus, this review aims to present a comprehensive view of the forage palm culture, emphasizing the properties, composition and applications of mucilage as a raw material for the development of coatings and edible films, contributing to the full use of this species in the context of bioeconomy and environmental sustainability.

2 THE CULTIVATION OF FORAGE PALM

Forage palm (*Opuntia* spp.) It belongs to the Cactus family (QUEIROZ et al., 2015), and this plant is widely distributed in Mexico and the South American continent. In Brazil, this culture was introduced at the end of the nineteenth century (QUEIROZ et al., 2015). The main cultivated species of forage palm are *Opuntia Indica Fig* and *Nopalea cochenillifera* (L.) Salm- Dyck. In the Brazilian semi-arid region, the number of localities producing this crop is around 125,725 properties (Figure 1) with its production in greater concentration in the states of Alagoas, Pernambuco and Paraíba (PEREIRA et al., 2015). For the Brazilian semi-arid region, this plant has high relevance, since it is one of the main crops used for the food supply of livestock in long periods of drought (PEREIRA et al., 2015).

Figure 1

Map of geographical distribution of forage palm producing properties, in the area of operation of Sudene



Source: Sudene, (2017).

The great adaptability to the semiarid regions of this crop is due to the morphophysiological characteristics that enable its survival in environments with water scarcity, high temperatures and low fertile soils (PEREIRA et al., 2015). Among them, the following stand out; the use of storage mechanisms of water and nutrients in the rainy season, to be used in the season of water scarcity. This mechanism is called crassulaceous acid, which allows the stomata to open at night for CO2 uptake and daytime stomatal closure, which reduces water loss through transpiration during the acquisition of inorganic carbon (LÜTTGE, 2004, 2010). In addition, the osmotic effect of the accumulation of organic acids allows the nocturnal acquisition of water from the transpiration stream, with the temporary storage of water in the vacuoles (LÜTTGE, 2010). These plants also have a network of fine roots close to the superficial layers of the soil (up to 10-20 cm), specialized for rapid absorption of water from light rains or even dew (SNYMAN, 2006). These characteristics give the forage palm aptitude to deal with low water availability and high solar radiation rate (LÜTTGE, 2004, 2010; PEREIRA et al., 2015), typical conditions of the semi-arid Northeast.

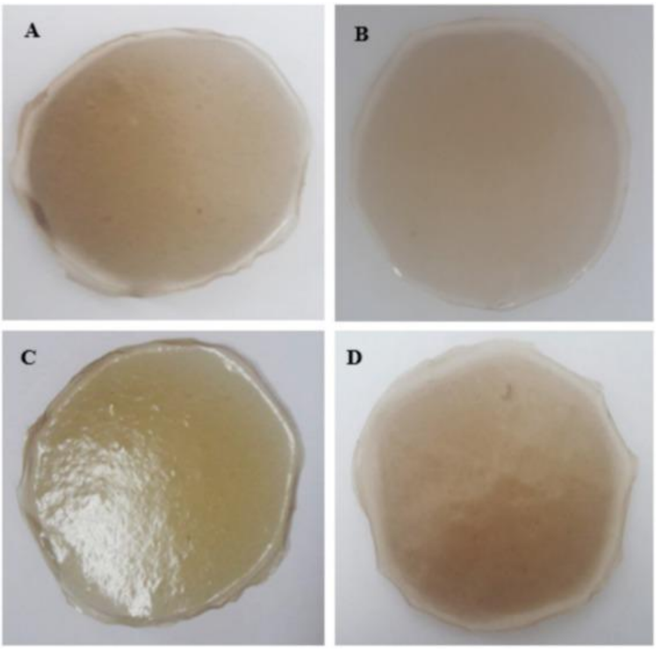
3 FORAGE PALM MUCILAGE

Polysaccharides from biomass derivatives, such as mucilage from different species, have stood out over synthetic polymers, due to the fact that they are derived from renewable, biocompatible and biodegradable sources (VALDÉS; GARRIGÓS, 2016). The mucilage of forage palm is obtained from cladodes, which is a heteropolysaccharide that has a high molecular weight and branched structure (SEPÚLVEDA et al., 2007), composed mainly of sugars such as arabinose, galactose, xylose (TRACHTENBERG; MAYER, 1981), it is considered by the industry to be a potential hydrocolloid because it has characteristics such as: viscosity, elasticity, emulsifying properties, capacity to retain water (MEDINA-TORRES et al., 2000; SÁENZ; SEPÚLVEDA; MATSUHIRO, 2004) and for having a translucent and amorphous appearance.

Forage cactus mucilage has the ability to swell when dissolved in water, forming colloidal and viscous suspensions (SEPÚLVEDA et al., 2007). Due to its polymeric matrix, it contains filmogenic and elastic properties (CONTRERAS-PADILLA et al., 2015), who can act as a barrier to water transfer, showing potential for use in the food industry, in the elaboration of coatings; In addition, mucilage is a raw material with biodegradability and toxicity (PRAJAPATI et al., 2013). When added to plasticizers, mucilage has greater potential for the elaboration of edible films (Figure 2), thus being considered a sustainable alternative also for the production of food packaging, replacing petroleum-derived plastic packaging (GHERIBI et al., 2018).

Figure 2

Cactus mucilage films plasticized with glycerol (A), sorbitol (B), PEG 200 (C) and PEG 400 (D)



Source: Gheribi et al., (2018).

4 PHYSICOCHEMICAL COMPOSITION OF MUCILAGE

The physicochemical composition of mucilage varies according to the species, the age of the cladodes and the edaphoclimatic conditions in which the cladodes are obtained (GEBRESAMUEL; TSIGE GEBRE-MARIAM, 2012). Monrroy et al., (2017) when extracting and characterizing the mucilage Opuntia cochenillifera (L.) Miller found that it contained an average of 40% carbohydrates, 7.4% crude protein, 1.6% nitrogen, 0.4% phosphorus, 1.2% potassium, 1.85% calcium and 0.35% magnesium. In addition, this study found that at concentrations of 1.4 and 6% the density values were 1.03, 1.03 and 1.05 g. mL−1, electrical conductivity was 2.3, 4.9 and 5.4 mS cm−1 and pH ranging between 4.8 and 5.0.

Sepúlveda et al., (2007) characterized the mucilage of Opuntia spp and found that it contained on average 5.6% moisture; 7.3% protein; 37.3% ash; 1.14% nitrogen; 9.86% calcium and 1.55% potassium. Jouki et al., (2013) found that when studying the mucilage obtained from quince seeds, it had 78.43% total sugar, 3.39% protein, 8.86% moisture, 6.71% ash and 1.98% fat content. Contreras-Padilla et al., (2016) studied the physicochemical and rheological properties (flow and deformation of the fluid) of mucilage and found that it is slightly acidic with a pH between 5.6 and 6, in addition to mucilage has non-Newtonian fluid behavior, high elastic properties, this behavior happens primarily at 100 days of maturity.

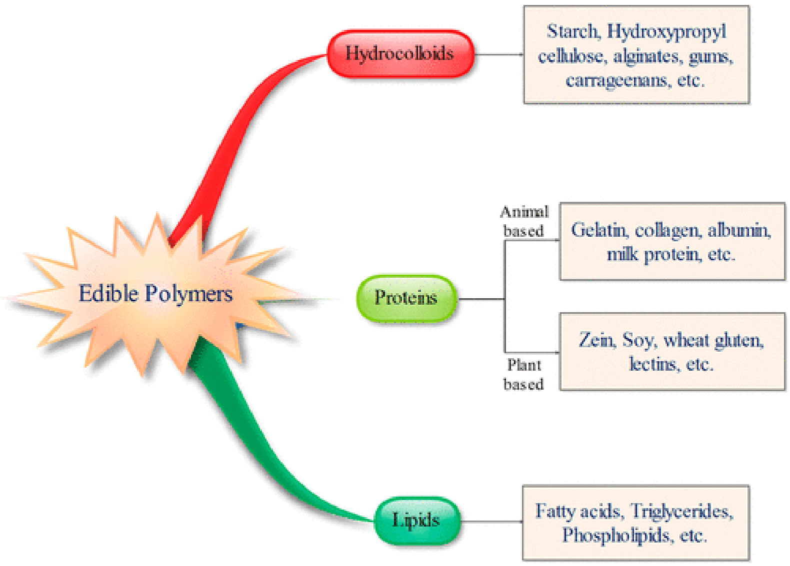
Mucilage is a compound that has a molecular weight ranging from 2.3 x 104 to 4.3 x106 g.mol-1. (CONTRERAS-PADILLA et al., 2015). Mucilage is composed of the sugars galactose, arabinose, galacturonic acid and glucose (ESPINO-DÍAZ et al., 2010). Medina-Torres et al., (2000) when studying the rheological properties of the mucilage of Opuntia ficus indica, observed a marked dependence of viscosity as a function of temperature, ionic strength and pH, in which as there is an increase in pH from acid to alkaline, there is an increase in viscosity, while with the increase in ionic strength there is a decrease in viscosity.

5 EDIBLE COATINGS AND FILMS

It is known that the food industry is increasingly interested in new technologies that act to increase the post-harvest life of food, such as the use of edible coatings, biocoatings and biofilms (ASSIS; BRITTO, 2014). Edible films are defined as a thin layer of edible material formed on a surface of a food. The main materials used for the formation of edible films are polysaccharides, proteins, and lipids (ESPINO-DÍAZ et al., 2010), thus the films are classified as: hydrocolloids, proteins, and lipids (Figure 3) (ALI; AHMED, 2018).

Figure 3

Different Categories of Edible Polymers and Examples



Source: Ali & Ahmed, (2018).

The use of this technology aims to extend the shelf life of food, providing a reduction in moisture loss, control of gas permeability and microbial activity, in addition to preserving the structural integrity of the tissues (ARVANITOYANNIS; PSIADOU; NAKAYAMA, 1996;

GHERIBI; HABIBI; KHWALDIA, 2019). Edible films with good mechanical properties have great potential to replace synthetic films, resulting in the reduction of environmental pollution because the films obtained are biodegradable (DEL-VALLE et al., 2005). Palm mucilage has the ability to form films, however, the film formed is brittle, brittle and not very flexible. Due to this, it is necessary to add plasticizers as they provide elasticity, resistance and maintain the physical integrity of the film formed. Glycerol, sorbitol, and polyethylene glycol are among the major plasticizers used in addition to mucilage to improve their mechanical and elastic properties (GHERIBI et al., 2018).

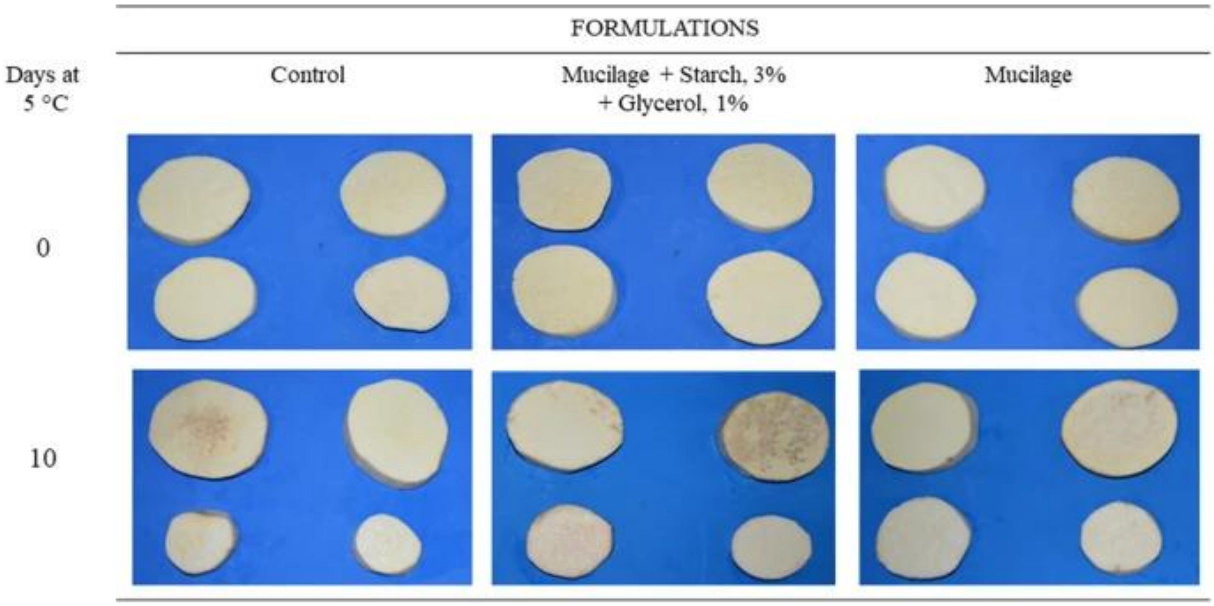
6 APPLICATIONS OF MUCILAGE IN FOOD PRESERVATION

Forage palm mucilage has become the raw material of studies in several areas. From 1982 to 2020, a total of 275 academic papers were published on this raw material, 70 of which were related to food technology and 31 to polymer studies (SCIENCE, 2020). Several studies have been developed on the use of forage palm mucilage as a raw material for the formulation of edible coatings. Del-Valle et al., (2005) used mucilage of *Opuntia ficus indica* as an edible coating to be used in the preservation of strawberries, and found that it proved to be efficient in maintaining physical integrity and sensory properties, extending the shelf life of the fruits, being a technology that can potentially reduce post-harvest losses.

Aquino et al., (2009) observed a protective function of mucilage combined with high concentrations of citric acid and sodium disulfide, since during drying there was a reduction in browning of bananas. Allegra et al., (2016) applied a palm mucilage-based coating to minimally processed kiwis and observed that it showed a tendency to maintain the bioactive compounds, firmness and reduce weight loss of the fruits, in addition to maintaining their visual quality. Damas et al., (2017) carried out a study in which they manufactured films using the mucilage of fruits of *Cereus hildmannianus* Plasticizers in different concentrations and verified that it has a promising potential for use as edible coatings to be applied in the food industry. In his study Gheribi et al., (2018) concluded that the addition of polyol plasticizers show significant effects on the mucilage films of *Opuntia ficus-indica*, being a sustainable alternative for the production of biodegradable food packaging to replace conventional plastic packaging. Morais et al., (2019) studied the mucilage of *Nopalea cochenillifera* (L.) Salm-Dyck as minimally processed yam edible coatings (Figure 4), and observed a reduction in fresh mass loss and a maintenance in visual and sensory quality, showing that the formulated edible coating is very promising for application in minimally processed roots.

Figure 4

Appearance of minimally processed yam coated with the following formulations: control; mucilage + starch, 3% + glycerol, 1% and mucilage. The slides were kept at 5 ± 2 °C for 10 days



Source: Morais et al., (2019).

7 FINAL CONSIDERATIONS

Forage palm stands out as a crop of extreme importance for semi-arid regions, due to its remarkable adaptation to conditions of water stress and high solar radiation, combined with its socioeconomic relevance in supporting livestock during periods of drought. Its physiological and structural characteristics, associated with the acid metabolism of crassulaceae (CAM), give it high efficiency in the use of water and storage capacity of essential compounds, making it a strategic species both from an agronomic and industrial point of view.

Among the compounds with the highest added value, the mucilage extracted from cladodes has aroused growing scientific interest for its physicochemical and functional properties. It is a natural, biodegradable, non-toxic and biocompatible polysaccharide, with an outstanding ability to form films and coatings, characteristics that make it promising for applications in the food industry and in the development of sustainable packaging. The use of this biomolecule in coatings and edible films has shown positive results in the postharvest conservation of fruits and vegetables, extending the shelf life and maintaining sensory and nutritional attributes of the products.

In view of this, forage palm mucilage represents a viable and environmentally sustainable alternative to synthetic polymers used in the food industry, contributing to the reduction of environmental impact and the strengthening of the regional bioeconomy. However, for its use to be expanded on an industrial scale, complementary studies are still needed to address the standardization of extraction methods, the influence of edaphoclimatic conditions on its composition, and the performance of different formulations in real food systems.

Thus, the valorization of forage palm and the full use of its compounds, such as mucilage, represent not only a strategy for the sustainable use of natural resources in the semi-arid region, but also an opportunity for technological innovation aimed at sustainability, food security, and adding value to a crop traditionally associated with resilience in the face of water scarcity.

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THE SOCIOBIODIVERSITY OF AGROFOOD SYSTEMS IN THE RIACHO DO MEL COMMUNITY, IRAQUARA, BAHIA

A SOCIOBIODIVERSIDADE DOS SISTEMAS AGROALIMENTARES DA COMUNIDADE RIACHO DO MEL, IRAQUARA, BAHIA

LA SOCIOBIODIVERSIDAD DE LOS SISTEMAS AGROALIMENTARIOS DE LA COMUNIDAD RIACHO DO MEL, IRAQUARA, BAHÍA

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ABSTRACT

The study aimed to understand the agricultural and social dynamics of a rural community by analyzing forms of labor organization, cooperation practices, and the use of local resources. The research was conducted in the quilombola community of Riacho do Mel, located in the municipality of Iraquara, Chapada Diamantina (Bahia, Brazil), through semi-structured interviews with 25 farming families, intentionally and stratifiedly selected to include different sectors of the residential nucleus and thus ensure spatial representativeness, as well as through the “snowball” sampling technique. The results indicate that local production is predominantly oriented toward self-consumption, sustained by essential crops such as corn, beans, cassava, and castor bean, and complemented by the diversity found in home gardens, which significantly contributes to the families’ food security.

Keywords: Agrobiodiversity. Traditional Communities. Extractivism. Family Farming.

RESUMO

O estudo teve como objetivo compreender a dinâmica agrícola e social de uma comunidade rural, analisando as formas de organização do trabalho, as práticas de cooperação e o uso dos recursos locais. A pesquisa foi desenvolvida na comunidade quilombola de Riacho do Mel, situada no município de Iraquara, Chapada Diamantina (BA), por meio de entrevistas semiestruturadas com 25 famílias agricultoras, selecionadas de forma intencional e estratificada, buscando contemplar diferentes setores do núcleo habitacional e, assim, garantir representatividade espacial bem como através da técnica “bola de neve”. Os resultados indicam que a produção local é predominantemente voltada ao autoconsumo, sendo sustentada por cultivos essenciais, como milho, feijão, mandioca e mamona, e complementada pela diversidade presente nos quintais, contribuindo significativamente para a segurança alimentar das famílias.

Palavras-chave: Agrobiodiversidade. Comunidades Tradicionais. Extrativismo. Agricultura Familiar.

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RESUMEN
El estudio tuvo como objetivo comprender la dinámica agrícola y social de una comunidad rural, analizando las formas de organización del trabajo, las prácticas de cooperación y el uso de los recursos locales. La investigación se desarrolló en la comunidad quilombola de Riacho do Mel, ubicada en el municipio de Iraquara, Chapada Diamantina (Bahía), mediante entrevistas semiestructuradas con 25 familias agricultoras, seleccionadas de manera intencional y estratificada para representar diferentes sectores del núcleo habitacional, garantizando así la representatividad espacial, así como a través de la técnica de “bola de nieve”. Los resultados indican que la producción local está predominantemente orientada al autoconsumo, sostenida por cultivos esenciales como maíz, frijol, mandioca y ricino, y complementada por la diversidad presente en los patios familiares, lo que contribuye significativamente a la seguridad alimentaria de las familias.

Palabras clave: Agrobiodiversidad. Comunidades Tradicionales. Extractivismo. Agricultura Familiar.

1 INTRODUCTION

Brazil stands out for its expressive diversity of native and cultivated plant species, which constitute both the basis of food and the main source of raw materials used by different social groups. This wide genetic variability, historically conserved and managed by farmers and traditional populations, results from a continuous process of selection and adaptation to local conditions. However, such practices and knowledge still lack greater appreciation and recognition, considering their essential role in maintaining productive autonomy and ensuring food security for rural and traditional communities (Brasil, 2006).

The concept of sociobiodiversity, formalized in 2009, comprises the articulation between goods and services originating from natural resources and the production chains associated with traditional peoples and family farmers (Diniz; Cerdan, 2017). Despite its social, cultural and economic relevance, the consumption of socio-biodiversity products is still limited, which highlights the need for policies and actions that encourage its commercialization and expand its presence in local markets. In this way, it is possible to strengthen short marketing circuits, preserve eating habits and cultural traditions, in addition to contributing to territorial development and the autonomy of producing families (idem).

According to Toledo and Barrera-Bassols (2015), biodiversity is a comprehensive concept that encompasses the variety of landscapes, types of vegetation, species and genes. For Diegues et al. (2000), this diversity is not only the result of natural processes, but also of cultural interactions and the management carried out by human societies. Thus, species become not only biological resources, but also symbolic, cultural and economic elements, integrating the daily life, productive practices and imagination of traditional communities.

The sustainability of traditional production systems depends fundamentally on the ability of farmers to ensure that the levels of biodiversity of managed ecosystems remain stable (Noda; Noda, 2016). The maintenance and cultivation of this genetic variability are currently practices conducted mostly by traditional farmers, who play an essential role in the conservation of genetic resources and the continuity of local ways of life (idem).

The diversity of cultivated plant species is determined by multiple factors, including the specific needs and demands of each family, the demands of the consumer market and traders, as well as aspects related to the origin, life history, and socioeconomic conditions of farmers (Figueredo et al., 2023). This plurality of motivations reflects the complexity of family agri-food systems, in which production aimed at self-consumption occupies a central place.

Production for self-consumption fulfills a fundamental principle of food security, by ensuring access to food in harmony with local eating habits and practices (Joseph; Rossetto, 2021). In addition to ensuring family food, this practice strengthens farmers' autonomy and resilience, reducing dependence on markets and the impacts of economic and environmental crises (Soares et al., 2018). At the same time, family farming is one of the main pillars of food security and sovereignty, responsible for a large part of the production of food for domestic consumption and for ensuring the permanence of populations in the countryside (Joseph; Rossetto, 2021).

Traditional agricultural practice has a multifunctional character, articulating cultural, environmental, food and economic dimensions. It performs functions ranging from the conservation of agrobiodiversity and the promotion of food and nutritional security to the sustenance of the cultural fabric and the socioeconomic base of the communities (Joseph; Rossetto, 2021). By valuing their socio-cultural heritage, such as knowledge, customs and traditions, farmers ensure their social reproduction and the continuity of their activities in the territory.

The management of agrobiodiversity by farmers is a strategic practice to ensure food security and sovereignty, as it expands the diversity of the food base at local and regional levels, stimulates the exchange of knowledge, and contributes to the conservation of genetic resources, such as seeds and seedlings, and traditional agroecosystems (Pereira et al., 2017). The knowledge and management practices developed in backyards and swiddens constitute a set of agri-food strategies aimed at guaranteeing food and the autonomy of rural communities. Such knowledge is fundamental for the effectiveness of food security, as long as it respects the ways of life and socio-environmental relations of each people (idem).

Agrobiodiversity, also called agricultural biodiversity, is the result of the interaction between the environment, genetic resources, management systems, and local knowledge, and is the result of a historical process that combines natural selection with artificial selection conducted by farmers (Ferreira, 2017). It is a section of biodiversity that expresses the relationships established between nature and culture, between traditional knowledge and productive practice, and is essential for the sustainability of agri-food systems (Machado et al., 2008).

According to Machado et al. (2008), agrobiodiversity is formed by the interaction of four interdependent elements: cultivation systems, species and varieties, human diversity and cultural diversity. The management of this diversity results in the conservation of local and traditional varieties, in the balance of crops and in the maintenance of cultural values, constituting a fundamental genetic and symbolic heritage for food sovereignty.

In this way, biodiversity encompasses both the natural and cultural domains, and it is through culture – expressed in the form of knowledge and practice – that traditional populations manage, enrich and preserve biodiversity (Diegues et al., 2000). Thus, understanding agrobiodiversity implies recognizing the central role of farmers in the conservation of biological and cultural diversity, as well as in sustaining local agri-food systems and their ways of life. In this context, the present study aimed to map the sociobiodiversity present in different traditional agroecosystems, such as backyards, gardens, pastures and managed forests, in the community of Riacho do Mel.

1.1 METHODOLOGICAL PROCEDURES

The research was conducted in the quilombola community of Riacho do Mel, located in the municipality of Iraquara, in the Chapada Diamantina region, Bahia. The study was based on the principles of social research, considering that the object of analysis of the social sciences is of a historical nature, since each society is constituted and organized in a unique way in a certain geographical and temporal space (Minayo et al., 2007).

The first stage consisted of carrying out a participatory mapping, based on ethnomapping techniques as described by Bandeira et al. (2018). Workshops were promoted in the community association, in which residents defined the boundaries of the territory for common use of the community; This activity made it possible to elaborate a territorial polygonal and visualize space through satellite images.

With the support of *Google Earth* and *Google Maps*, an estimate of the number of families residing in the community was carried out, totaling approximately 243 family units. Among these, 25 farming families were selected in an intentional and stratified way, seeking to contemplate different sectors of the housing nucleus and, thus, ensure spatial representativeness. In addition, the "snowball" technique was used (Vinuto, 2014), in which the research began with a farming family indicated by community residents, who, in turn, indicated other families, and so on.

Data collection was conducted through semi-structured interviews, applied with the help of two forms: one addressing general information about the family and the other specifically focused on agricultural crops and production practices. The interviews were conducted with farmers who voluntarily consented to participate in the study, by signing the Informed Consent Form (ICF).

The interviews took place in the participants' homes and, when authorized, direct surveys were carried out in the backyards and gardens of the families. In these visits, the locations were georeferenced using GPS (Global Positioning System). The tabulation and quantitative analysis of the data were performed with the Microsoft Excel software, while the identification of the cultivated species and varieties was made based on local knowledge, therefore, of ethnovariities, and based on bibliographic consultations in the specialized literature.

2 RESULTS AND DISCUSSION

In all, 25 interviews were conducted with people whose ages ranged from 36 to 84 years. Of these, 68% were male and 32% female. The number of residents per household ranged from one to six people, with the highest percentage (36%) corresponding to two residents. This data shows the reduction in the number of residents in the houses of rural communities.

The crops most cited by the families and cultivated on a larger scale by the research participants were beans (*Phaseolus vulgaris and Vigna unguiculata*), cassava (*Manihot esculenta* Crantz), corn (*Zea mays*), castor bean (*Ricinus communis*) and banana (*Musa spp*.). Coffee (*Coffea arabica*), sugarcane (*Saccharum spp*.) and pineapple (*Ananas comosus*) were also mentioned, to a lesser extent, cultivated both for consumption and animal feed and for commercialization. Pereira et al., (2017, p. 17) highlight that:

The ethnospecies cultivated in gardens, such as beans, cassava and corn, are fundamental because they are available in more periods and allow long-term storage, in relation to cassava, the production of flour and other derivatives also works as a strategic reserve, attenuating the meaning of food shortage in periods of scarcity.

In addition to these crops, oranges (*Citrus* spp.) and mangoes (*Mangifera indica*) were frequently mentioned, although they have a low number of individuals, as they are perennial species generally grown in backyards and intended for family consumption. This fact corroborates the statement by Barbosa et al. (2023) that the diversification of production in backyards directly contributes to strengthening food security and promoting autonomy in obtaining food. In addition, backyard crops can also represent an important source of income generation, since farmers have the possibility of selling surplus production (Carneiro et al., 2013).

In all, approximately 153 ethnovarieties of cultivated plants were identified, covering staple foods such as beans, corn, cassava and commercial foods such as castor beans – which make up the basis of local production – as well as vegetables, fruit trees, medicinal plants and Non-Conventional Food Plants (PANCs) (Tables 1 and 2). Some of these species showed wide internal diversity. Fruits represent a fundamental part of the diet, as they provide significant amounts of essential vitamins and minerals (Carneiro et al., 2013). The relevance of the native plants mentioned is also highlighted, recognized as an integral part of the culture and heritage of the populations of each region (Jacob et al., 2020).

As families maintain the practice of saving seeds from the previous crop for the next planting, there is an important contribution to the conservation of local varieties. These varieties constitute the basis of family farming and food sovereignty, as they represent a genetic heritage of tolerance and resistance to different types of stress and adaptation to local environments and management (Machado et al., 2008).

Few varieties are cultivated by a larger number of families; among them, corn, cassava, beans and castor beans, which make up the basis of local agriculture and are characteristic of the swiddens of the community of Riacho do Mel. The other varieties are cultivated by fewer families, according to the particularities of each domestic group, evidencing an idiosyncratic variation of local agricultural systems. As observed by Santos et al. (2017) in the Laranjeira I Settlement, located on the edge of the Pantanal of Cáceres – MT, the main purpose of the agricultural activity practiced by the farmers of Riacho do Mel is also self-consumption. As production is mostly aimed at self-consumption, family food preferences are the criterion that, in general, defines which species and varieties will be cultivated (Joseph; Rossetto, 2021)

Table 1

Ethnovarieties of crops from traditional agroecosystems (backyards, gardens, pastures and managed forests) cited by the research participants (n = 25), in the Riacho do Mel community, Iraquara, Bahia

Ethnovarieties	Ethnovarieties	Ethnovarieties
Avocado	Pineapple Pernambuco	Alligator squash
Acerola	Yellow cassava	Cassava cocoa

Eucalyptus cassava	Butter cassava	Black butter cassava
Black cassava	White root cassava	Purple cassava
Mulberry	Andú	Rice
Banana caturra	Banana Coffee	Maranhão banana
Banana nanica	Silver Banana	White Potato
Cassava potatoes	Pink potato	Purple potato
Sweet gourd	Coffee	Cane 190
White or Caiana cane	Caiana cane	Black caiana cane
Vulture cinnamon cane	Cana fista	Yellow fista cane
Black fista cane	Cana maria pelada	Cane without thorn
Pink cane	Capiaçu grass/ cutting	Bittergrass (native)
Anapiê cutting grass	Brachiaria grass	Cutting grass
Grass flu	Mombasa grass	Purple grass
Evergreen grass	Tanzania grass	Carambola
Caxia/Caxi	Bahia coconut	Broad bean
Calango beans	Arranca beans	Purple/Purple Bage Beans
Carioca beans	Carioquinha beans	Picker beans
Cucurinha beans	String beans	Pink beans
Purple beans	White guava	Red guava
Soursop	Orange spike	Water orange
Ponkan orange	Orange navel	Galician lemon
Yellow papaya	Japanese papaya	Papaya
Castor bean coca	Castor bean maringá	Castor bean
Small castor bean	Castor bean from the Northeast	Castor bean paraguaçu
Painted castor bean	Painted black castor bean	Black castor bean/ banana
Black castor bean/	Black castor bean	Castor bean evergreen
Red castor bean	White cassava	Wild white cassava
Castilian cassava	Jatoba cassava	Cassava parakeet tongue
Cassava	Cassava maria preta	Cassava eye of the forest
Cassava black eye	Cassava black eye of the forest	Cassava plant
Black cassava	Purple cassava	Cassava tazinha
Red cassava	Import Mango	Sword sleeve
Palm sleeve	Manga papo roxo	Pink sleeve
Yellow passion fruit	Maxixe	Watermelon coconut
Round watermelon	Fine cob corn	Girl's palm
Bird pepper	Chili pepper	Pine cone
Surinam cherry	Okra	Seriguela

Tamarind	Umbu	

Source: Authors, 2024.

Table 2

Ethnovarieties of vegetables, medicinal plants and PANCs of the traditional agroecosystems cited by the research participants in the Riacho do Mel community, Iraquara, Bahia

Vegetables	Medicinal	Unconventional food
Lettuce	Carapiá (tea)	Jackfruit
Coriander	Black dick	Licuri
Onion	Cotton	Jabuticaba
Cabbage	Barbatimão	Cow's tongue
Bell pepper	Bilberry	Purslane
Arugula	Carobinha	Mangaba
Parsley	Dandá	Palm
	Fennel	Cherry tomato
	Mint	Bredo
	Maria aninha	Ora-pro-nóbis
	Moringa	Cajá
	Mucugê	Cambuí (native)
	Stonebreaker	Guava
		Graviola/ Ticum da serra (native)

Source: Authors, 2024.

The results also reveal a general pattern of variation in the diversity of crops in the swiddens of Riacho do Mel, in which few varieties are cultivated by a greater number of families, namely: corn, cassava, beans and castor beans. In this way, this combination constitutes the basis of local agriculture, characterizing the community's gardens: or standard systems (model) of cultivation. The other varieties mentioned, for the most part, are cultivated by a smaller number of families, representing individual or family preferences (idiosyncratic variation).

Corn was mentioned by more than half of the interviewees, being a crop widely cultivated in the community and used both for family consumption and for the commercialization of grains and animal feed. However, it is not known whether more than one family cultivates the same variety, due to the high proportion of respondents who could not identify it, probably due to the prolonged use of hybrid varieties purchased in local markets or government programs.

According to Emperaire (2005, p. 33), cassava is one of the main sources of carbohydrates and its production is associated with food autonomy. Of the ethnovarieties of cassava (*Manihot esculenta* Crantz), butter cassava was mentioned by 40% of the interviewees, even in the face of the high diversity of varieties existing in the community. This highlights the importance of cassava for the local population, as its varieties are widely used: the cooked tuber is consumed by families (such as the cassava butter ethnovariety), the parts of the plant are destined for animal feed, and the processed tuber is used in the production of flour and tapioca, both for consumption and for commercialization. Similar results were observed by Joseph and Rossetto (2021) in the District of Mimoso – Municipality of Santo Antônio de Leverger, MT, where cassava is considered a central food in the diet, being also an important source of income and planted both for *fresh* consumption and for the manufacture of by-products (flour, cakes, among others), which complement the diet of families.

Andu beans and fava beans are also cultivated by many families in the fields and backyards, although in smaller quantities. According to the interviewees, andu beans are generally planted around the plantations and intended for family consumption, being one of the crops present in almost all properties. This fact corroborates the study developed by Carneiro et al. (2013) in the Alegre Settlement, municipality of Quixeramobim-CE, in which it is highlighted that the primary purpose of productive backyards is to generate food for family self-consumption.

Common beans, in turn, have a great diversity of varieties in the community, and the most cited varieties that are part of local agrobiodiversity were purple bagé beans (or purple bagé) and rosinha beans, often cultivated in intercropping with castor beans and corn. These varieties are mainly aimed at self-consumption, being sold only when there are surpluses, which occurs less frequently due to the low productivity associated with periods of drought.

Castor bean was also widely mentioned by the interviewees and is part of the most common polyculture system in Riacho do Mel. As it is a crop with a production cycle of 6 to 12 months, polyculture is an agricultural strategy that, in addition to promoting benefits to the soil, allows the combination of crops with different cycles, expanding the supply of food and products for commercialization over time. Castor bean has a great diversity of varieties in the community, with black castor bean being the most cited. Its cultivation is exclusively intended for commercialization: farmers sell the grains in 60 kg bags to middlemen, with prices varying according to the period of sale.

Some farmers also intercrop coffee with pineapple or coffee with cassava. Coffee is grown mainly for self-consumption, and the families that produce it in larger quantities also sell the dry beans in the years of higher productivity. The artisanal process of preparing coffee powder is carried out with manual roasting and grinding of the beans in a wooden mortar.

Sugarcane showed a high diversity of varieties, concentrated, however, in a few swiddens, with cayan cane being the most cited. Some producers grow sugarcane for animal feed, especially cattle, while others sell it through the sharecropper system for the production of cachaça and rapadura in neighboring communities. In this type of trade, half of the production is with the producer and the other half with the owner of the still.

Another crop with emphasis on varietal diversity was grasses, used in animal feed. These species are usually cultivated in pastures or in intercropping with other grass varieties, being cut for direct supply to the animals. An example of polyculture reported was the intercropping of grass with banana trees.

Some families also maintain the cultivation of vegetables in their backyards for their own consumption. Barbosa et al. (2023) recognize that agroforestry backyards are important spaces for family and social coexistence, built and transformed mainly by women, in an activity that represents the extension of their historical role of caring for the domestic environment. In addition, these spaces contribute significantly to the preservation of agrobiodiversity (Carneiro et al., 2013).

In the community's traditional agroecosystems, medicinal plants and non-conventional food plants (PANCs) are found (Chart 2); Few conventional vegetables were mentioned by the research participants, with lettuce and coriander being the most mentioned. All are grown in family backyards, intended for self-consumption, although some farmers also distribute them to friends and neighbors.

The use of plants with medicinal and herbal properties forms one of the main bases that define a diet as sustainable (Jacob et al., 2020). Among the medicinal plants, both species cultivated in backyards and gardens and native species or those that sprout spontaneously in cultivated areas were identified; The most cited were caapiá and picão-preto, generally used in the preparation of medicinal teas.

Native plants have great potential to enrich and diversify the food sources available to local populations (Jacob et al., 2020), in addition, they represent a crucial resource of local agrobiodiversity (Figueredo et al., 2023). The most mentioned Non-Conventional Food Plants (PANCs) were jackfruit (*Artocarpus heterophyllus*), licuri (*Syagrus* spp.), jaboticaba (*Plinia* spp.) and cow's tongue, all native species of the region. From jackfruit and jabuticaba, the fruits are consumed *in natura*, and jaboticaba is also used in the production of liquor, both for family consumption and for commercialization. From the licuri, some families consume the fruit *in natura* and use the leaves in the making of handicrafts, such as bags. Cow's tongue, as well as purslane, palm, bredo and cherry tomato, is used in the preparation of meals, complementing the diet of some families.

The results of this research are in line with the study carried out by Santos et al. (2022), which points to the consumption of fresh food plants as the predominant form, followed by preparation methods that involve the application of heat, such as cooking, roasting, and the production of sweets.

Of the 25 families interviewed, 92% have agriculture as their primary activity. Among the secondary activities, cattle raising, trade in bars, artisanal production and occasional work in third-party gardens (in the form of sharecroppers) stood out. The average area of the swiddens was approximately 3 hectares (ha), ranging from 0.2 ha to 17.2 ha. These areas range from plantations of domesticated species to areas of preserved vegetation and pastures. Most of the swiddens belong to the families themselves, as well as in the District of Mimoso (Joseph; Rossetto, 2021) while others are ceded for cultivation, in which case production is shared with the landowner.

The production systems are mostly located in areas far from the urban core, where the residences are concentrated. Some crops, however, are carried out in small areas in backyards, in these spaces, there is a greater presence of fruit and medicinal plants, a result similar to that found by Barbosa et al. (2023).

To prepare the soil before planting, some families hire machinery to carry out plowing and harrowing, and maintenance cleaning is done with hoes. Others carry out all the handling manually, using hoes and sickles. The use of coivaras to clear the swiddens is not a recurrent practice among the families.

The soils of the swiddens vary according to the location, being described by farmers as oak soils, general soils, clayey soils of red or yellow color and sandy soils. The most common conservation practice is the covering of the soil with crop residues, recognized by many farmers as important for the protection, conservation and fertility of the soil, in addition to contributing to moisture retention. In this sense, residues and leaves from corn, castor bean, cassava and sugarcane crops are left in the soil, being used as organic fertilizer or mulch.

In addition, it is common to plant legumes between crops, as a way of enriching the soil, and the practice of intercropping is widely adopted in the community. The polyculture system most practiced by the farmers interviewed is the intercropping between corn, beans and castor beans, although corn is also cultivated in association with cassava. This system represents a strategic choice, as it optimizes production and constitutes an advantageous alternative in scenarios where the spaces destined for cultivation are reduced (Santos et al., 2017).

The use of industrial agricultural inputs is infrequent among the interviewees, only one family reported using NPK 4:14:18 fertilization in beans, watermelon and corn crops. In addition to vegetable residues, some farmers use cattle manure to fertilize fruit and vegetables. Approximately half of the interviewees adopt the practice of leaving the soil fallow, usually during the dry season, waiting for the beginning of the rains for the new planting.

Of the swiddens analyzed, 84% are conducted in a rainfed system, which negatively impacts productivity during periods of drought, causing significant losses to farming families. As an alternative, many choose to plant "in the rainy seasons", which usually occur from October to the beginning of the following year. Few crops are destined for commercialization, especially in rainfed gardens; Sales occur only when there are surpluses, which is rare due to low productivity in dry seasons. In view of this, pensions and social programs become fundamental for the food security of families.

In addition to the reduced number of residents, the active workforce in the fields is also limited. The largest proportion (40%) corresponds to families with only two active people, usually couples or parents and children. Some interviewees highlighted that young people's interest in agriculture has decreased, since many seek other economic activities, including outside the community. This trend contributes to the reduction of the intergenerational transmission of agricultural knowledge, breaking the cycle of reproduction of traditional knowledge and practices, which represents a risk to the preservation of the community's biological and cultural heritage (Brasil, 2006).

The reduced number of people involved in agricultural activities in families generates the need to occasionally hire external workers to perform tasks such as planting, weeding, plowing and harrowing the soil. Among the families interviewed, 33% stated that they hire occasional labor, either because the residents are elderly and can no longer carry out all the activities in the fields, or because there is a demand for work that exceeds the family's capacity. A result higher than that found by Joseph and Rossetto (2021) in the District of Mimoso – Municipality of Santo Antônio de Leverger, only 5% used hired labor due to barriers such as the high cost of this type of labor and the lack of people interested in the work. On the other hand, some families do not hire workers, as agricultural production does not generate enough profit to pay for external labor. There are also those composed exclusively of elderly people, who resort to hiring casual workers to maintain their production.

Collective actions, such as the "change of working day", are not common practices among the interviewees, being reported by only a few families. When they occur, they usually occur between family members, such as children and siblings who live in different houses and share the work in the fields, or between neighbors who have greater affinity. These actions usually occur in periods that require greater demand for labor, such as harvest seasons or in the construction of fences; this practice was also observed in the study conducted by Joseph and Rossetto (2021).

When asked about the exchange of agricultural materials, such as seeds, seedlings and cultivated products, many families initially answered that this practice did not occur. However, throughout the interviews, several participants reported sharing some crops and materials with neighbors, family and friends. Of note is the change of maniva or "manaiba", a term popularly used to designate the piece of cassava stem used in vegetative propagation, a common practice in the community, since it is the main form of multiplication of cassava, usually planted soon after the tubers are harvested.

Half of the families interviewed have some type of animal husbandry, such as cattle, chickens, pigs, fish or goats. These creations are mainly intended for self-consumption, and are eventually marketed. Chicken eggs are usually consumed and artisanal production of dairy products, such as cheese and sweets, which are sold to supplement the family income. The aggregation of value to milk, through its artisanal processing into derivatives, is a key factor to strengthen the production system, since it makes dairy farming economically viable, allowing it to remain under the management and control of the farming family. (Gavioli; Costa, 2011).

Extractivism is a complementary activity of income, but it presents low commercial demand due to the little development of local productive arrangements aimed at native species (Diniz; Cerdan, 2017). In this context, only one family interviewed reported working with extractive activities, selling products obtained from cambuí, mangaba (*Hancornia* sp.)

and licuri (*Syagrus* spp.). For Figueiredo et al. (2023), by exploiting native species as a source of income through family farming, they become a key element to boost the sustainable development of the region. According to Gavioli and Costa (2011), this practice can be understood as a biodiversity management strategy, representing a form of conservation of natural resources with potential for expansion and indicating, at the same time, a greater proximity of farmers to their ecological environment.

3 FINAL CONSIDERATIONS

The results obtained show that the community of Riacho do Mel has an expressive agrobiodiversity, as a result of the traditional practices of cultivation and management maintained by the farming families. Production, focused on self-consumption, is supported by essential crops such as corn, beans, cassava and castor beans and complemented by the diversity of backyards (fruit, PANCs, medicinal), which guarantees local food security.

Despite the strong presence of family farming, there was some dissatisfaction among the participants regarding the low productivity, especially in periods of drought, which ends up discouraging the continuity of planting. Local agricultural production is mostly focused on self-consumption, and the surpluses destined for commercialization have a low economic return, making family income dependent on external sources, such as pensions and social programs. Simultaneously, the aging of the population and the rural exodus decrease the available workforce, threatening the intergenerational transmission of agricultural knowledge and putting at risk the future sustainability of the community's biocultural heritage.

Finally, the participatory mapping process proved to be an effective tool to identify and record the biological and food diversity existing in the different agrifood systems of the community. In addition, the material produced contributes to giving visibility to local socio-biodiversity, strengthening the recognition of the territory and traditional knowledge, both among the residents themselves and with the surrounding society.

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LIVING LABS IN BRAZILIAN AGRIBUSINESS: AN ANALYSIS OF THE POTENTIAL FOR OPEN INNOVATION AND CO-CREATION IN NEMATODE CONTROL BASED ON THE STOLLER, LMPP, AND USINA SÃO LUIZ CASE STUDY

LIVING LABS NO AGRONEGÓCIO BRASILEIRO: UMA ANÁLISE SOBRE O POTENCIAL DE INOVAÇÃO ABERTA E COCRIAÇÃO NO CONTROLE DE NEMATOIDES COM BASE NO ESTUDO DE CASO STOLLER, LMPP E USINA SÃO LUIZ

LIVING LABS EN EL AGRONEGOCIO BRASILEÑO: UN ANÁLISIS DEL POTENCIAL DE INNOVACIÓN ABIERTA Y COCREACIÓN EN EL CONTROL DE NEMATODOS A PARTIR DEL ESTUDIO DE CASO STOLLER, LMPP Y USINA SÃO LUIZ

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ABSTRACT
This article analyzes the application of the Living Labs model in the context of Brazilian agribusiness, highlighting its ability to promote open innovation, sustainability, and co-creation among public, private, and academic actors. The research uses as its empirical object the experiment developed through a partnership between Stoller, the Plant Monitoring and Protection Laboratory (LMPP), and Usina São Luiz, focused on nematode management. The study seeks to understand how the Living Lab methodology contributes to collaborative innovation processes from the perspective of field experimentation and the integration of scientific knowledge with productive practice. The analysis concludes that agricultural Living Labs represent a new paradigm of systemic and sustainable innovation in the sector by integrating technical-scientific knowledge with the practical expertise of rural producers.

Keywords: Living Labs. Agribusiness. Open Innovation. Sustainability. Nematodes.

RESUMO
O presente artigo analisa a aplicação do modelo de Living Labs no contexto do agronegócio brasileiro, destacando sua capacidade de promover inovação aberta, sustentabilidade e

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cocriação entre atores públicos, privados e acadêmicos. A pesquisa toma como objeto empírico o experimento desenvolvido em parceria entre a Stoller, o Laboratório de Monitoramento e Proteção de Plantas (LMPP) e a Usina São Luiz, voltado ao manejo de nematoides. O estudo busca compreender de que forma a metodologia Living Lab contribui para processos colaborativos de inovação, na perspectiva da experimentação em campo e da integração entre ciência e prática produtiva. Conclui-se que os Living Labs agrícolas representam um novo paradigma de inovação sistêmica e sustentável no setor, ao integrar o conhecimento técnico-científico com o saber prático do produtor rural.

Palavras-chave: Living Labs. Agronegócio. Inovação aberta. Sustentabilidade. Nematoides.

RESUMEN

El presente artículo analiza la aplicación del modelo de Living Labs en el contexto del agronegocio brasileño, destacando su capacidad para promover la innovación abierta, la sostenibilidad y la cocreación entre actores públicos, privados y académicos. La investigación toma como objeto empírico el experimento desarrollado en colaboración entre Stoller, el Laboratorio de Monitoreo y Protección de Plantas (LMPP) y la Usina São Luiz, orientado al manejo de nematodos. El estudio busca comprender de qué manera la metodología Living Lab contribuye a los procesos colaborativos de innovación desde la perspectiva de la experimentación en campo y de la integración entre el conocimiento científico y la práctica productiva. Se concluye que los Living Labs agrícolas representan un nuevo paradigma de innovación sistémica y sostenible en el sector, al integrar el conocimiento técnico-científico con el saber práctico del productor rural.

Keywords: Living Labs. Agronegocio. Innovación Abierta. Sostenibilidad. Nematodos.

1 INTRODUCTION

In recent decades, the concept of Living Lab has been consolidated globally as an open innovation methodology capable of articulating different social actors around collaborative experimentation and the development of solutions capable of meeting real demands of society. In agribusiness, this approach has been gaining relevance due to its ability to integrate scientific knowledge with production practice and the demands of the field. In this sense, the present research seeks to understand how the application of the Living Lab methodology in the agricultural context of the joint experiment between Stoller, LMPP and Usina São Luiz can contribute to the generation of knowledge and innovation applied to Brazilian agribusiness.

According to Mitchell (1996), the creation of the first Living Labs dates back to the end of the twentieth century, in the context of the development of information and communication technologies, in addition to their integration into the urban environment and daily life. In the agricultural sphere, the concept, however, responds to the secular scientific project of Rural Extension, created in the British academy in the nineteenth century and globalized in the following centuries, with the intention of establishing an educational process — and later also communicative (Freire, 1992) — in which the focus is on transmitting scientific knowledge to farmers and ranchers to promote, above any other objective, the expansion of the productivity of their plantations and livestock (Peixoto, 2008). In this sense, in the 2000s, agricultural Living Labs began to emerge, notably in European territory, with the initial objective of meeting specific economic and social issues in the field, consolidating themselves from 2015 onwards as environments for experimentation and innovation focused on productivity, sustainability, and the use of advanced technologies, according to Schaffers, Merz, and Guzman (2009) and Hossain, Leminen and Westerlund (2012).

In Brazil, however, the concept has been little explored, with just over 10% of the works on Living Labs dedicated to the approach of the agricultural segment[8]. In addition, there are few experimental studies that demonstrate the applicability of the concept and these, in turn, focus on regions such as Rio Grande do Sul (Silva, 2025) and Mato Grosso do Sul (Silva & Costa, 2018), lacking experimentation in states such as São Paulo, which occupies the first position in the national ranking of agricultural production, with a Gross Production Value

[8] Data derived from conceptual research carried out on the Google Scholar platform, on November 2, 2025, which shows that there are more than 15,800 articles on Living Labs written by Brazilians, but less than 1,900 of them are on the agricultural aspect.

(GVP) of R$ 159.25 billion achieved in 2024 (Brasil, 2024, p. 2). In this context, in which the concept is recent and little explored in the country, especially in strategic regions, the present work is justified by the fact that it proposes to demonstrate how the application of the methodology could contribute to Brazilian cultures and the approximation of scientific knowledge with the field, generating an increase in productivity and technological advancement.

Through empirical research, we specifically intend to demonstrate how the implementation of an agricultural Living Lab, in the experiment with nematodes in sugarcane at the São Luiz Plant, enables the generation of applicable scientific data and technological solutions that contribute to the productivity and sustainability of the sector. Thus, the present work aims to contribute to the academic literature, demonstrating the practical applicability of the Living Lab methodology in the Brazilian context and reinforcing the importance of empirical experiences as a basis for the formulation of more efficient management practices and innovation strategies in agribusiness.

Thus, the structure of the article is organized in order to present the concepts of theoretical basis and the evolution of the Living Lab model, followed by the adaptation of the model to the agricultural context, the problem of nematodes for Brazilian agriculture and the detailed description of the empirical case study, including methods, results, discussion and final considerations.

2 THE CONSOLIDATION OF LIVING LABS TO APPLY SCIENCE IN REAL CONTEXTS

The concept of Living Lab emerged in the 1990s (Mitchell, 1996), linked to the idea of creating collaborative spaces for experimentation and innovation based on real contexts of use, with its development driven especially by research movements focused on promoting open innovation and responding to direct user demands, thus understanding how people interact with products, services and technologies in everyday situations. To establish the conceptual basis of Living Labs, the present work is based on the definition of Hossain, Leminen and Westerlund (2012), authors for whom Living Labs are constituted as innovation ecosystems based on public-private-personal partnerships, which involve end users as active co-creators in development and validation processes.

Throughout the 2000s, the model achieved an institutional development through the European Network of Living Labs (ENoLL), which organized and certified living labs in Europe. In this sense, according to ENoLL (2020), a Living Lab consists of a co-creation environment in which companies, universities, governments, and citizens collaborate for the development, prototyping, and validation of innovations in real environments. Thus, unlike a conventional scientific laboratory, the Living Lab is not restricted to the physical space of research, also seeking to insert itself in the daily life of society, making the innovation process more inclusive and participatory.

Thus, the main characteristic of Living Labs is their emphasis on the active participation of the user, who is no longer a mere receiver of technologies and starts to act as a co-producer of knowledge, a principle aligned with Chesbrough's (2003) open innovation model, according to which ideas can arise inside or outside organizational boundaries, and must move freely between institutions. The Living Lab, in this context, works as a mediator between science, market, society and government, following a quadruple helix model that favors the creation of solutions more adapted to local realities.

From a methodological point of view, Living Labs operate in interactive cycles of design, experimentation, evaluation, and reconfiguration, in which continuous experimentation allows testing hypotheses and adjusting solutions dynamically, as highlighted by Ballon and Schuurman (2015) when they delimit that it is this characteristic that is responsible for distinguishing Living Labs from traditional forms of R&D, Considering that knowledge is produced in situations and in direct interaction with the contexts of use, which expands the validity of innovations and, at the same time, strengthens collective learning among the actors involved.

It should be noted that in this scenario, the diversity of actors involved, as listed by the quadruple helix model, gives Living Labs a hybrid and intersectoral character. As a way of classifying the nature of Living Labs, Hossain, Leminen, and Westerlund (2012) propose a typology that categorizes them according to the predominant type of leadership: user-centered, business-driven, led by public institutions, or coordinated by community networks, with each type reflecting different power dynamics, objectives, and forms of governance.

In the global context, Living Labs have been incorporated into innovation policies, especially in European Union countries, as tools to promote regional development and digital transformation (Katzy, 2012). Its decentralized and collaborative logic allows innovation strategies to be adapted to territorial specificities, which reinforces their relevance to emerging and rural contexts, such as agribusiness, as pointed out by Zavratnik, Superina and Stojmenova Duh (2019, p. 2):

Living Labs are spaces for research, development, and innovative and participatory activities, which use multidisciplinary approaches and promote the paradigm of co-creation. (…) They are considered one of the fundamental building blocks for smart rural development and an important step towards creating a Smart Village environment[9]

The literature points out that Living Labs contribute to the democratization of innovation by creating spaces for dialogue between diverse knowledges and by recognizing that innovation is not only technological, but also social, thus establishing a redefinition of the role of different actors in the development ecosystem, which is particularly relevant in Latin American countries, where social and productive inequalities require participatory and inclusive approaches.

We are not unaware, however, that criticisms of the model have also emerged, mainly related to the difficulty of measuring results and the maintenance of collaboration between actors with different interests. According to Schuurman, De Marez and Ballon (2016), the sustainability of Living Labs depends on the ability to balance research demands with the practical needs of users and the strategies of partner companies, which requires transparent governance and clear mechanisms for sharing results, highlighting the relevance of studies such as this article, which demonstrate in detail what has been achieved.

Thus, the consolidation of the Living Lab model as an open innovation instrument has expanded its scope of application to various areas, including education, health, smart cities and, especially, agriculture, a sector addressed in the subsequent chapter.

3 LIVING LABS IN THE AGRICULTURAL CONTEXT

The consolidation of the Living Lab concept in the agricultural context stems from the growing need to articulate innovation, sustainability, and social participation in field-oriented experimentation processes (Bouwma *et al*., 2022). In Brazilian agribusiness, the integration between scientific research, technological knowledge and local knowledge is strategic to face complex challenges, such as climate change, environmental pressures, increased productivity and pest management, such as nematodes addressed in this article. In this scenario, agricultural Living Labs present themselves as interactive and collaborative environments that allow testing and validating technological solutions directly in real

[9] Living Labs are spaces for innovative and participative research, development and activities that use multidisciplinary approaches and promote the co-creation paradigm. (...) They are seen as one of the important building blocks of smart rural development and an important step towards establishing a Smart Village environment.

cultivation conditions, promoting co-creation between producers, companies, academic institutions, and public policy development agencies.

In this sense, we have rescued the European movement started in 2006, which aimed to support innovative projects through the creation of interactive ecosystems and provided the basis for the institutionalization of Living Labs on a global scale through the European Network of Living Labs (ENoLL), created to regulate, organize and certify living labs, establishing operating standards and fostering the use of these environments as intermediaries for innovation, capable of generating social and technological development (Dutilleul, 2010; Galli, 2010). Specifically for the agricultural context, ENoLL offers implementation parameters that allow the adaptation of the model to rural territories, connecting different actors and promoting experimental practices with real impacts on productivity and sustainability.

In this context, Dutilleul (2010) highlights that it is possible to identify five dimensions that characterize Living Labs and apply to agricultural environments, namely: innovation systems formed by multidisciplinary networks that promote collaboration; real-time monitoring of social and productive environments; direct involvement of users in the creation and testing of solutions; organizations that facilitate, maintain, and offer relevant technological infrastructure and services; and focus on the co-creation of applied knowledge. Together, these elements structure the agricultural Living Lab model, creating conditions for rural producers to act as active agents of innovation and validate practices and technologies in their own productive contexts.

The logic of collaborative participation is reinforced by the aforementioned quadruple helix model, proposed by Del Vecchio *et al.* (2017), in which universities, companies, government and society are mobilized to share knowledge and experiences. In the field, this articulation translates into an environment in which farmers, researchers, and agricultural technicians interact to identify real problems, propose solutions, conduct experiments, and adjust management practices on an ongoing basis, generating applicable and economically viable results. Hakkarainen and Hyysalo (2016) highlight that the interaction between end users, researchers and companies in Living Labs forms a unique level of knowledge aggregation, accelerating the materialization of innovations and increasing the effectiveness of applied technological solutions. In the agricultural context, this approach allows, for example, the development of integrated nematode management strategies, in which technical-scientific knowledge is tested and validated in partnership with rural producers, promoting mutual learning and strengthening local capacities.

We also add to this elucidation, the organizational point of view, demarcated by Nesterova and Quak (2016) who propose four essential roles within a Living Lab: Owner, responsible for managing, organizing and monitoring the laboratory; Users, who test solutions in the field; Customers, who benefit from the results; and Stakeholders, which offer technical and institutional support. The application of this structure in agribusiness allows each actor to contribute in a defined and coordinated way to the innovation cycle, ensuring that experimentation is relevant, efficient, and aligned with productive and socio-environmental objectives.

We thus emphasize that the need for continuous innovation in Brazilian agribusiness, a protagonist in the global agricultural market, makes Living Labs particularly relevant in facing recurring challenges related to pest and disease management, environmental degradation, climate variations and production efficiency. In this context, the implementation of living laboratories offers a controlled but real environment to test technologies such as biopesticides, advanced irrigation systems, soil monitoring, and agroecological practices, allowing solutions to be adjusted to local conditions before their large-scale adoption.

In addition, agricultural Living Labs promote social and territorial innovation, strengthening relationships between producers, communities, and research institutions (LIVERUR Project Fact Sheet, 2018), which is fundamental for Brazilian agribusiness, which operates in diverse biomes and faces inequalities in the distribution of resources and access to technologies. Thus, the co-creation and sharing of knowledge between local, regional, and academic actors allows sustainable and efficient practices to be disseminated in a contextualized way, increasing the resilience of production chains.

In the case study involving Stoller, LMPP and Usina São Luiz, the implementation of an agricultural Living Lab enabled the experimentation of integrated strategies for nematode management in sugarcane, with continuous monitoring of the results in the field. The approach demonstrated that the model not only contributes to the generation of technological solutions, but also promotes collective learning, facilitates the adaptation of innovations to specific contexts, and creates a space for dialogue between science and productive practice, strengthening the relationship between producers and researchers, as shown in the subsequent section.

4 CASE STUDY: THE FIGHT AGAINST NEMATODES EXPERIENCED BY THE UNION BETWEEN STOLLER DO BRASIL, LMPP AND USINA SÃO LUIZ

The challenges of contemporary agriculture, such as the increase in global demand for food, the pressure for sustainability, and the scarcity of natural resources (Bayer, 2024), require new approaches to the generation and validation of applied knowledge. In this scenario, Agricultural Living Labs represent an innovative alternative for collaborative experimentation that connects research, technology, and agricultural practice in a real environment. Unlike traditional experiments conducted under controlled conditions, Living Labs take place in the production context itself, where multiple actors, such as producers, companies, researchers, and public agents, participate in the co-creation, testing, and validation of technological solutions. This approach, aligned with the paradigm of open innovation (Chesbrough, 2003), seeks to accelerate the cycle of knowledge circulation (Almeida, Placca & Luvizotto, 2025), reducing the distance between the laboratory and the field and promoting shared learning.

Especially in the agriculture sector, the Living Lab model has been gaining prominence for allowing innovations to be evaluated under real soil and climate conditions, incorporating environmental, operational and socioeconomic variables. Thus, as established, this article aims to discuss the concept and operation of Living Labs in the agricultural sector, presenting a practical case of application, based on the collaborative experiment aimed at the biological control of nematodes in sugarcane (*Saccharum officinarum*) and produced through a partnership between the Plant Monitoring and Protection Laboratory (LMPP) of FATEC Pompeia "Shunji Nishimura", the input technology solutions company Stoller do Brasil and the São Luiz de Ourinhos/SP Plant.

4.1 NEMATODES AND THEIR IMPACT ON AGRICULTURE

Nematodes are vermiform organisms widely distributed in the soil, in freshwater and saltwater environments, and may have free habits, predators, or parasites of insects, animals, and plants (Pinheiro, 2022). In the agricultural context, its diversity is particularly significant, encompassing species that perform beneficial functions, such as the decomposition of organic matter and nutrient cycling, to phytoparasitic species, called phytonematodes, which attack roots and other parts of plants, harming vegetative development and productivity (Pinheiro & Biscaia, 2019).

Phytonematodes are classified as endoparasites or ectoparasites, depending on their form of feeding. Endoparasites, such as root-knot nematode, penetrate roots and induce gall formation, inhibiting the flow of water and nutrients and causing dwarfism, chlorosis, and plant wilting. Root-lesion nematodes, on the other hand, penetrate and move inside the roots, causing necrotic lesions that compromise nutrient absorption and can facilitate the entry of secondary pathogens. Others, such as the garlic yellow nematode, attack internal tissues, causing cell disintegration, chlorosis and rotting of the bulbs. The reniform nematode mainly affects the aerial part, resulting in severe dwarfism and reduced productivity. The yam black-barked nematode compromises the tubers, causing lesions that depreciate the commercial value and favor the attack of other pathogens, while the spiral nematode usually feeds externally, and can, in high infestations, significantly reduce the absorption of water and nutrients (Pinheiro, 2017; Pinheiro & Biscaia, 2019).

Figure 1

Table With Nematode and Vegetable Species Preyed on

Common Name (genus)	Relevant Species in Sugarcane	Damage and Compromise of Production	Damage Potential (Severity)	Observations
Root-lesion nematode (*Pratylenchus*)	*P. zeaeP. Brachyurus*	Main damage: Necrosis (dark spots) and death of roots. It causes sprouting failures (reboleiras), less tillering, drastic reduction of ratoon longevity and facilitates the entry of fungi (e.g. Fusarium).	+++	Considered the genus with the greatest economic impact and most widespread in sugarcane fields in Brazil. P. zeae is the most common.
Root-knot nematode (*Meloidogyne*)	*M. javanicaM. Incognita*	Main damage: Formation of galls (bumps) that prevent the absorption of water and nutrients. It causes rickets, yellowing and underdevelopment.	++	Highly harmful, especially in ratoons. The occurrence of visible galls facilitates diagnosis in the field.

Spiral nematode (*Helicotylenchus*)	*H. dihystera*	Ecto/endoparasite (attacks from the outside and from the inside). It causes superficial lesions and necrosis. Reduces root volume.	+	It is rarely the main problem, but it occurs in high populations and contributes to the overall decline of ratoon, compounding the damage of others.
Ringed nematode (*Criconemella*)	C. (*Mesocriconema*) spp.	Ectoparasite. It feeds on the tips of the roots, causing thickening and paralysis of root growth. The plant has fewer "fine roots".	+	Frequently found in soil analyses. Its damage is less direct, but it contributes to plant stress.
Dagger nematode (*Xiphinema*)	*Xiphinema* spp.	Ectoparasite. It feeds on the tips of the roots, causing necrosis and swelling (without forming typical galls).	+	It is best known for being a vector of viruses in other crops (e.g., grapevine), but in sugarcane it causes direct damage through feeding, reducing the efficiency of the roots.

Source: Prepared by the authors.

The economic impact of these organisms is significant, considering that globally, it is estimated that phytonematodes cause losses of 12 to 14.6% in tropical and subtropical crops, with losses that exceed US$ 173 billion annually (Elling, 2013; Nicol et al., 2011). In Brazil, losses reach about R$ 35 billion, especially in vegetable and fruit crops (Machado, 2015; Ravichandra, 2014; Rao *et al*., 2016 *apud* Pinheiro & Biscaia, 2019), an impact that highlights the need for efficient management strategies, with special attention to the growing demand for quality produce and the importance of food safety.

On the other hand, nematodes can also play a positive role as bioindicators of environmental and soil quality. Its sensitivity to variations in temperature, CO_2 concentration and soil management allows it to monitor edaphoclimatic changes and assess the impacts of agricultural practices on sustainability (Ritzinger, Fancelli & Ritzinger, 2010). In this way, they provide valuable data for adjustments in cropping systems, integrating productive and environmental aspects into agricultural management.

In the Brazilian context, characterized by the diversity of biomes, edaphoclimatic variations and inequality of access to technologies, the study of nematodes highlights a paradox: at the same time that they represent a significant economic threat, they constitute a strategic tool for soil monitoring and for the implementation of more sustainable agricultural practices. It is in this scenario that agricultural Living Labs gain relevance, by allowing the experimentation of integrated management methods, such as the biological control of nematodes and other technologies in the context of integrated management, in real field conditions, promoting the co-creation of solutions between producers, researchers and companies, and strengthening social and territorial innovation in the sector.

4.2 STOLLER, LMPP AND SÃO LUIZ MILL EXPERIENCE

Between March 2024 and May 2025, the authors of the present work carried out a collaborative experiment involving LMPP, Usina São Luiz, located in the municipality of Ourinhos/SP, and Stoller do Brasil, configuring an exemplary model of agricultural Living Lab that involves academic, agro-industrial and business stakeholders, respectively. The objective was to evaluate the efficacy of the Enraíze + Root Top protocol, created by Stoller do Brasil and whose composition is based on the combination of plant hormones, humic acids and the biological nematicide *Pochonia chlamydosporia*, aiming at the control of nematodes in sugarcane plant. The study was carried out in a productive area of 10.57 hectares, under real operating conditions, involving the co-creation and circulation of knowledge between researchers, plant technicians and specialists from the partner company.

The experimental design was established in strips, with three replications and three different treatments: control (without using the protocol), Stoller treatment (Stimulate + Rizotec + Root Top) and the standard treatment of the mill, which uses products such as Quartz and Fertilactyl Cana+. Each strip contained eighteen planting rows, with a spacing of 1.5 meters, totaling 27 meters wide and an extension equivalent to the workability of the plot. In each range, ten georeferenced points were defined for soil and root sampling, as well as for manual biometric measurements. It is worth noting that this experimental model was proposed by the LMPP researchers and accepted by the companies (Stoller and Usina), following the operational routines of the field.

Figure 2

Application ranges (9 ranges) with the treatments studied in sugarcane plant, at USL, Ourinhos/SP, ondo: T – control, Stoller – Stoller Treatment and USL – Mill Standard Treatment

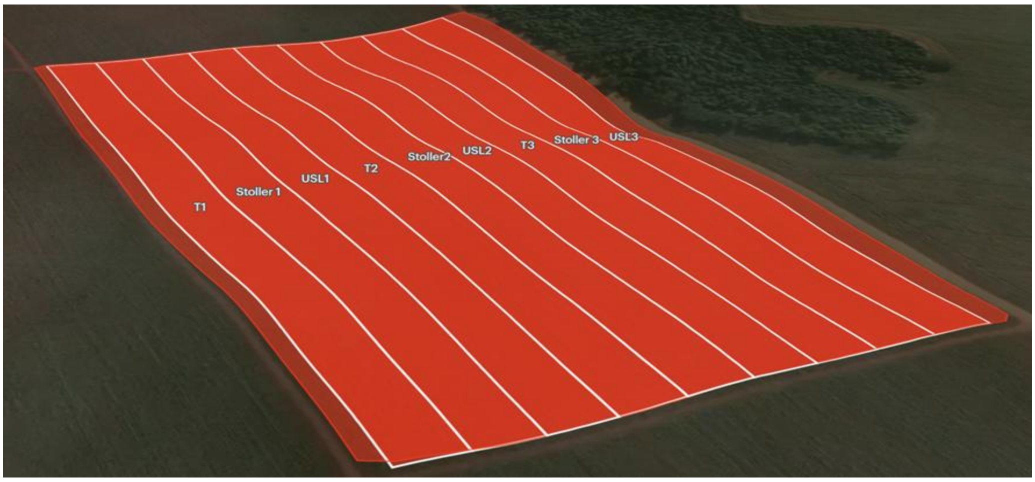


Figure 3

Georeferenced points for the collection of 90 nematologic samples in the ranges of treatments in plant cane and manual biometry, at USL, Ourinhos/SP

Collections occurred before the application of the products and again at 60 and 140 days after treatment, following classical methodologies for extraction and counting of nematodes (Jenkins, 1964; Coolen & D'here, 1972). At the same time, satellite images were collected using the OneSoil and Google Earth Engine platforms, and a flight was carried out with an eBee X multispectral drone, equipped with a Micasense RedEdge camera, to obtain orthophotos and calculate vegetation indices, such as NDVI (Normalized Difference Vegetation Index), NDRE (Red Edge Index) and GLI (Green Foliage Index). The combined use of these tools allowed the monitoring of plant vigor and the comparative analysis between treatments in an objective and georeferenced way, an innovation of the experimental model of the LMPP including digital analysis.

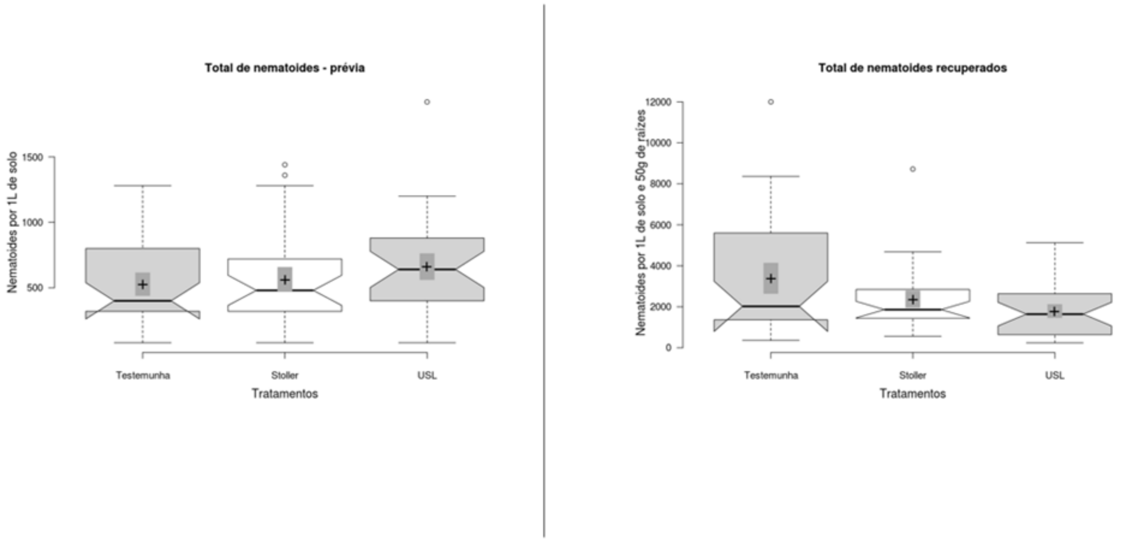
The results indicated a significant reduction in nematode populations in the treatments that received the products from Stoller and the Plant, with emphasis on the Enraíze + Root Top protocol. The total population of phytonematodes fell by 47.1% sixty days after application, and maintained 15.8% of residual control at 140 days, a performance superior to conventional management. The nematode *Pratylenchus zeae*, the main species observed in the area, showed a reduction of 40.4% in the Stoller treatment, while the Plant treatment reached 56.1% control, confirming the efficiency of the combined use of bioinputs and plant hormones.

Manual biometry of the plants at 60 days revealed significant differences in vegetative development, with greater height and tillering in the Stoller treatment, which was also reflected in satellite and drone images, which showed higher NDVI indices in these ranges. The digital analyses showed that vigor and vegetation cover were superior for the Stoller treatment, reaching an average of 52% coverage, compared to 47% in the Plant standard and 45% in the control. Remote sensing monitoring also made it possible to follow the growth curve of the sugarcane field and identify periods of stress, such as the one recorded between September and October 2024, reinforcing the role of digital tools as real-time agronomic diagnostic instruments.

In the harvest, carried out in May 2025, the Stoller treatment obtained an average productivity of 148.1 tons of sugarcane per hectare (TCH), surpassing the control (137.2 TCH) and the standard treatment (144.6 TCH). In addition, it had the highest value of Total Recoverable Sugars (ATR), with 140.2 kg/t, and the best result of Tons of Sugar per Hectare (TAH), with 20.7. The statistical analyses confirmed the significance of the results and indicated greater productive uniformity between the treated ranges, which reinforces the reliability of the experimental methodology applied in a real environment. The subsequent graph illustrates the results obtained, demonstrating significant control of nematodes.

Figure 4

Statistical analysis in comparative boxplot of the total number of nematodes recovered in the sampling prior to and 60 days after the application of the treatments in the ranges. + = average. Gray bar = confidence interval of the mean (83%). ----- = median. Notch = median significance (95%) (Chambers; Cleves & Frazier, 1983)



4.3 DISCUSSION OF RESULTS

The case of Usina São Luiz demonstrates how the Living Lab model expands the frontiers of agricultural research, by integrating science, technology and productive practice in the same innovation ecosystem. Throughout the experiment, the constant interaction between researchers, technicians, and producers created a continuous learning process, in which partial results were discussed collectively and interpretations shared. This collaborative dynamic allowed for real-time methodological adjustments and consolidated experimentation as a living, participatory and data-driven process.

In this sense, the use of digital technologies was decisive for the success of the experiment, especially with regard to the OneSoil and Google Earth Engine platforms that enabled the temporal monitoring of the crop and the correlation between climatic data and vegetation indices, while the processing of multispectral images in QGIS provided detailed analyses of vegetation cover and vigor. This integration between remote sensing tools and manual data collection has set up a hybrid model of agricultural research, which combines scientific rigor and immediate applicability.

More than product validation, the application of the Living Lab methodology at the São Luiz Plant demonstrates the ability to generate contextualized knowledge, aligned with the edaphoclimatic and socioeconomic particularities of the region. In this model, the producer, represented by the agroindustry and partner farmers, ceases to be a passive recipient of technologies and assumes an active role in the development of innovative solutions, strengthening the integration between research and rural extension. We thus emphasize that constant interaction between science and practice allows not only the improvement of products, such as the Root + Root Top protocol, but also the adaptation of nematode management strategies to the specific conditions of the soil, climate, and cultivated varieties, accelerating the adoption of more sustainable and efficient practices.

We also highlight that the Living Lab model favored the integration between actors of different scales, consolidating knowledge networks that include producers, researchers, agricultural technicians and public managers. This social and territorial dimension is essential in the Brazilian context, characterized by the diversity of biomes, inequality of access to technologies, and challenges related to environmental sustainability. The co-creation of solutions in a real environment allows innovations to be evaluated not only in terms of agronomic efficiency, but also in terms of socio-environmental impact and economic viability, reinforcing the concept of agriculture 4.0 as an integrated system of production, monitoring and intelligent management.

5 FINAL CONSIDERATIONS

The experiment conducted at the São Luiz Plant robustly evidences the potential of agricultural Living Labs as strategic instruments for open innovation, co-creation and generation of contextualized knowledge in Brazilian agribusiness. Experience has shown that it is possible to combine applied research, production practice and advanced digital technologies to produce significant results in productivity and sustainability, in real field conditions, reducing the time between development and application of solutions.

In the specific case of the Root + Root Top protocol, the 47.1% reduction in the phytonematode population at 60 days and the residual control of 15.8% at 140 days, combined with productivity gains of up to 148.1 TCH and an increase in ATR and TAH, illustrate how the Living Lab methodology can provide reliable and applicable data for strategic management decisions. Such results confirm the efficiency of the hybrid model that integrates remote sensing, manual collection and statistical analysis, allowing real-time monitoring of vegetative growth, soil cover and plant vigor.

In addition to technical performance, the study highlights the value of the collaborative innovation model, in which producers, technicians and researchers actively participate in experimentation and interpretation of results. This approach strengthens the transfer of knowledge between academia and the productive sector, consolidates territorial learning networks, and contributes to the construction of agricultural practices adapted to the edaphoclimatic and socioeconomic conditions of the state of São Paulo, the country's main agricultural hub, with a GVP of R$ 159.25 billion in 2024 (Brasil, 2024, p. 2).

The study reinforces that the implementation of Living Labs in the context of São Paulo, and more broadly in Brazil, can serve as a basis for the development of the Smart B100 Science Center for Development (CCD SB100), [10]a project of the São Paulo Research Foundation (FAPESP) that aims, among other objectives, to establish bases for the formation of an agricultural Living Lab focused on optimizing soil management and pest control and nematodes. By creating environments of continuous and digitized experimentation, the CCD-SB100 will be able to consolidate replicable methodologies that connect science, technology, and productive practice, promoting open innovation, collective learning, and co-creation between different actors in the agro-industrial ecosystem.

Finally, the results obtained corroborate the idea that Living Labs constitute a new frontier of agriculture 4.0, by uniting sustainability, applied science, and competitiveness in the same production system. By strengthening the integration between research and extension, generating contextualized knowledge and accelerating the adoption of innovative practices, these living laboratories offer a strategic alternative to address critical challenges of Brazilian agribusiness, such as nematode management, soil degradation and production efficiency, consolidating themselves as essential instruments for systemic and territorial innovation in the sector.

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[10] The SB100 CCD will build a digital platform — called Smart B100 (SB100), through generative artificial intelligence (AI) technologies — to disseminate scientific knowledge that is part of Bulletin 100, a publication of the Agronomic Institute (IAC) that provides rural producers in the territory of São Paulo with information and recommendations on fertilization and soil liming, essential factors for crop management in the field.

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SEVEN
publicações acadêmicas

RURAL DEVELOPMENT AND TOURISM: EMPLOYMENT AND INCOME OPPORTUNITIES FOR YOUNG PEOPLE IN RURAL AREAS

DESENVOLVIMENTO RURAL E TURISMO: OPORTUNIDADES DE EMPREGO E RENDA PARA JOVENS EM ÁREAS RURAIS

DESARROLLO RURAL Y TURISMO: OPORTUNIDADES DE EMPLEO E INGRESOS PARA JÓVENES EN ZONAS RURALES

https://doi.org/10.56238/sevened2025.039-008

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ABSTRACT
Recent transformations in the relations between rural and urban areas have redefined the economic and spatial organization of the countryside. Among the factors driving these changes, the growing expansion of agribusiness plays a central role, causing profound shifts in the labor market, economic dynamics, and population distribution. One of the most notable outcomes of this process is the significant outmigration of young people from rural areas, both as a place of residence and as a space for professional insertion. In this context, this article—based on a literature review, questionnaires, and semi-structured interviews—analyzes rural tourism as a potential means of breaking with the concentration-driven logic of agribusiness, highlighting non-agricultural activities (beyond animal and plant production) as an alternative to encourage young people to remain in rural areas as a place to live and work. The empirical evidence obtained from the data indicates that rural tourism can diversify income sources, generate new opportunities—especially for women and young people—and strengthen local social networks by expanding the functions of rural properties to include non-agricultural activities, among them tourism. Despite its potential, the advancement of rural tourism depends on the implementation of adequate public policies and the adoption of training and management strategies. The study focuses on the municipality of Ituiutaba (MG), a context in which such initiatives show the capacity to promote a more inclusive, sustainable, and sustained model of rural development.

Keywords: Rural Development. Tourism. Youth. Permanence. Ituiutaba (MG).

RESUMO
As transformações recentes nas relações entre campo e cidade têm redefinido a organização econômica e espacial do meio rural. Entre os fatores que impulsionam essas mudanças, a crescente expansão do agronegócio desempenha papel central, provocando modificações profundas no mercado de trabalho, na dinâmica econômica e na distribuição populacional. Um dos reflexos mais marcantes desse processo é a saída expressiva de jovens das áreas rurais, tanto como lugar de vida quanto como espaço de inserção profissional. Nesse contexto, este artigo, fundamentado em revisão bibliográfica,

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questionários e entrevistas semiestruturadas, analisa o turismo rural como uma possibilidade de ruptura com a lógica concentradora do agronegócio, apontando as atividades não agrícolas (para além da produção animal e vegetal) como alternativa para estimular a permanência dos jovens no meio rural, como local de morada e trabalho. As evidências empíricas obtidas através dos dados indicam que o turismo rural pode diversificar as fontes de renda, gerar novas oportunidades, especialmente para mulheres e jovens e reforçar as redes sociais locais, ao ampliar as funções das propriedades para atividades não agrícolas, entre elas o turismo. Apesar do seu potencial, o avanço do turismo rural depende da implementação de políticas públicas adequadas e da adoção de estratégias de formação e gestão. O estudo toma como recorte o município de Ituiutaba (MG), contexto em que tais iniciativas demonstram capacidade para promover um modelo de desenvolvimento rural mais inclusivo, sustentável e sustentado.

Palavras-chave: Desenvolvimento Rural. Turismo. Juventude. Permanência. Ituiutaba (MG).

RESUMEN

Las transformaciones recientes en las relaciones entre el campo y la ciudad han redefinido la organización económica y espacial del medio rural. Entre los factores que impulsan estos cambios, la creciente expansión del agronegocio desempeña un papel central, provocando profundas modificaciones en el mercado laboral, en la dinámica económica y en la distribución poblacional. Uno de los efectos más destacados de este proceso es la marcada salida de jóvenes de las áreas rurales, tanto como lugar de vida como de inserción profesional. En este contexto, este artículo—basado en revisión bibliográfica, cuestionarios y entrevistas semiestructuradas—analiza el turismo rural como una posibilidad de ruptura con la lógica concentradora del agronegocio, señalando las actividades no agrícolas (más allá de la producción animal y vegetal) como una alternativa para estimular la permanencia de los jóvenes en el medio rural, como espacio de vivienda y trabajo. Las evidencias empíricas obtenidas a partir de los datos indican que el turismo rural puede diversificar las fuentes de ingresos, generar nuevas oportunidades—especialmente para mujeres y jóvenes—y reforzar las redes sociales locales al ampliar las funciones de las propiedades para actividades no agrícolas, entre ellas el turismo. A pesar de su potencial, el avance del turismo rural depende de la implementación de políticas públicas adecuadas y de la adopción de estrategias de formación y gestión. El estudio toma como recorte el municipio de Ituiutaba (MG), contexto en el cual tales iniciativas demuestran capacidad para promover un modelo de desarrollo rural más inclusivo, sostenible y sostenido.

Keywords: Desarrollo Rural. Turismo. Juventud. Permanencia. Ituiutaba (MG).

1 INTRODUCTION

An interesting debate on the definition [definitions] of the rural is practically endless, but the literature points to a certain consensus on the following elements: I - rural is not necessarily synonymous with agricultural [animal and vegetable production] and rural is not always synonymous with agricultural; II - the rural is not exclusively sectoral (pluriactivity) and multifunctional (productive, environmental, ecological, social functions, etc.); III - rural areas tend to have relatively low population density considering urban areas (in the surroundings or not); IV - there is no absolute isolation between rural and urban areas. Different networks, mercantile, social and institutional, are interconnected between the rural and the urban. Another complex point in rural studies is the very proposition [or propositions - in the plural] about rural development and the discussion itself (often naturalized) about development.

The endogenous or exogenous approaches or a combination of the two within the context of rural development proposals gives a good idea of the plurality of empirical situations to deal with this development perspective: local characteristics, external forces, institutions (and their arrangements), the limits of the modernization paradigm, the various approaches to the rural (including beyond the agricultural), etc. The multifunctionality of rural spaces (productive functions, role in ecological balance and support for recreation activities and preservation of the landscape) force us to consider that nature conservation, Ecological and Rural Tourism, Agrotourism, organic agriculture, among others, show a perspective of multifaceted rural development, including relations between the rural as a consumption space for populations living in urban areas, or the criterion to define which urban it is. Rural areas may lose their primary function of animal and plant production, and others become valued (landscape, tourist and ecological functions). However, there is no rural development "without agriculture; there is no agriculture and no farmer without other activities; and there are no other activities without the development of small and medium-sized towns and cities". (KINSELLA et al., 2000, p. 484). However, when considering public policies for rural spaces, in the Latin American experience, including Brazil, there is a change in the conduct of these policies: from the promotion of economic growth based on the stimulus to the modernization of agriculture, after the Second World War (without great concern for the environmental dimension of the rural), to a new perspective of valuing rural territories and a multifunctional character of these spaces.

Research on rural and urban social universes has presented social, economic and cultural dynamics that point to the weaknesses (present, for example, in the principles of rural sociology) about a certain dual nature of the rural and urban worlds, sustained by a set of oppositions. Among these oppositions there would be mainly a set of agricultural activities (practiced in rural areas) and commercial, industrial and service activities (concentrated in the urban world).

However, the relations between the countryside and the city have undergone intense transformations, driving new economic and spatial dynamics. Among these changes, the expansion of agribusiness stands out, which causes significant changes in rural areas, especially in the labor market, in the economy, and in population dynamics. One of the most evident effects is the exodus of young people from rural areas, whether as a place of residence or professional activity. This article, based on a literature review, questionnaires and semi-structured interviews, discusses rural tourism as an alternative to the exclusionary logic of hegemonic projects, including agribusiness, aiming at the permanence of young people in the countryside, considering the rural as a place of work and home. The data reveal that rural tourism can generate economic opportunities, especially for young people and women, in addition to strengthening the local social fabric, with the management of properties beyond agriculture (animal and vegetable production) directed to non-agricultural activities, as an emblematic example of rural tourism. However, its development depends on effective public policies, training and management strategies. The study has as a spatial cut Ituiutaba (MG), where these practices have the potential to promote a more sustainable and inclusive rural development, in a scenario of spatialization of agribusiness, especially the spatial circuit of sugarcane and extensive and intensive dairy farming.

Promoted in the Brazilian experience since the mid-twentieth century, the modernization of agriculture was structured based on a set of state policies and programs, altering rural spaces in a concentrated, selective and unequal way. It aimed to increase agricultural production and productivity through technological innovations (which were spreading internationally in the context of the so-called Green Revolution (Matos; Pessôa, 2011). Brazilian economic thought widely disseminated in this period is based on the logic of the classic roles of agriculture in economic development (Delgado, 2001). To fulfill these basic functions of agriculture, a broad technological modernization was promoted, which intensely modified production in the Brazilian countryside, as well as the relations between capital and labor and the countryside and the city (Matos; Pessôa, 2011) and a very limited perspective of rural development and with a management of properties deeply associated with the increase in agricultural production and productivity.

At the turn of the century, the diverse and distinct socio-spatial configurations of agribusiness (Elias, 2003) and its new spatialities (Baeninger, 2023), pose new questions for studies on rural development. Changes that occurred in the processes of industrialization, urbanization and, more recently, productive restructuring, resulted in new dynamics (economic, social, political and cultural) causing profound transformations in the relations between the countryside and the city (Hespanhol, 2013). The municipality of Ituiutaba (MG) is characterized by growing productive specialization, modernization of very selective agriculture, favoring medium and large rural producers and centered mainly by the concentration in the spatial circuit of sugarcane production and land. As an unequal and excluding modernization, there was a broad process of rural exodus (migration from the countryside to the cities) and an unequal and excluding modernization in the experience of Ituiutaba.

The increase in production and productivity was not a condition to promote the well-being of the population. It solved agricultural problems, but favored land and income concentration. Canales and Canales Ceron (2013), when analyzing the interrelations between urbanization, globalization of agriculture and the international division of labor, consider the emergence of a new development model in Latin America, in which rural spatialities are strengthened that break with the traditional rural-urban flows.

The agropolization paradigm combines a pattern of urban residence with a dynamic of agrarian-export accumulation, inducing the formation of a wide variety of agrarian cities where global links are densified through the production and processing of commodities (Canales and Canales Ceron, 2013) with branches of the agro-industrial sector's production chain that intertwine in the commercial branches, banking/credit and services, agroprocessing, logistics/transportation to meet the demands of modern agriculture that install new agricultural crops or restructure agricultural production with the presence of physical technology with emphasis on agricultural machinery, chemistry with partial replacement of labor by the application of herbicides and biotechnology and the genetic improvement of plants, Among others, by productively and spatially metamorphosing agricultural production, in the Brazilian experience, many cities have become a reference for the reproduction of capital associated with agribusiness, organized to meet the consumption needs of agribusiness and its demands (technical systems, services, agricultural credits, etc.).

The "agribusiness cities" are transformed into dynamic centers of capital reproduction in different economic spheres. Particularly in the municipality of Ituiutaba, one of the largest producers of commodities, Baeninger and Ojima (2008), the dynamics of agribusiness reproduction emerges as a phenomenon connected with global productive restructuring, articulating it, locally, with the production of regional urban-rural arrangements (dis)articulating at different scales (Demétrio, 2017). In Ituiutaba, public policies aimed at rural development with a largely productivist character, that is, the countryside only as a place to produce, and were not concerned with social factors, such as the quality of life and the diversity existing in the rural, including productive. From 1990 onwards, however, these aforementioned policies began to be elaborated based on the territorial perspective, reinforcing the local scale (Hespanhol, 2007). About the rural is practically endless, but the literature points to a certain consensus on the following elements: I - rural is not necessarily synonymous with agricultural [animal and vegetable production] and rural is not always synonymous with agricultural; II - the rural is not exclusively sectoral (emphasis on non-agricultural activities) and multifunctional (productive, environmental, ecological, social functions, etc.); III - rural areas tend to have relatively low population density considering urban areas (in the surroundings or not); IV - there is no absolute isolation between rural and urban areas. Different networks, mercantile, social and institutional, are interconnected between the rural and the urban. Another complex point in rural studies is the very proposition [or propositions - in the plural] about rural development and the discussion itself (often naturalized) about development. It is understood that rural development must consider the various dimensions, including social, cultural, political and environmental. It is in this sense that this text will deal with the rural beyond the agricultural with a focus on rural tourism and agritourism in the context of Ituiutaba (MG).

2 DEVELOPMENT

The rural exodus and the scarcity of job opportunities represent challenges that compromise the sustainability of rural communities in different experiences, whether Brazilian or international. The migration of young people and women to urban centers not only reduces the availability of labor in the countryside, but also threatens the preservation of the cultural and social traditions of these localities (Carneiro, 1998; Abramovay, 2003). In this scenario, the strengthening of sustainable economic initiatives, such as rural entrepreneurship, tourism, and agritourism, emerge as promising strategies to transform this reality, offering new possibilities for socioeconomic development (Schneider; Gazolla, 2008).

According to Bricalli (2005), tourism in rural areas comprises all enterprises that provide recreation, leisure and any other activity related to tourism, as long as they are located in rural areas. The literature on rural tourism in Brazil highlights its relevance in the revitalization of local economies, environmental conservation, and the preservation of the cultural identity of rural communities (Trentin, 2019; Bianchi et al., 2020).

Tourism is an activity in constant transformation, driven by new demands from the public and growing competition in the market. This scenario favors the emergence of different tourist modalities, including rural tourism, which is consolidated as an alternative capable of increasing the income of rural landowners, in addition to valuing traditional ways of life, the characteristics of rurality and contact with nature. According to the Ministry of Tourism, rural tourism is all activities practiced in non-urban areas, which consists of leisure activities in rural areas in various modalities defined based on the offer: Rural Tourism, Ecological Tourism or Ecotourism, Adventure Tourism, Business Tourism and Events, Health Tourism, Cultural Tourism, Sports Tourism, activities that complement each other or not. In addition, rural tourism plays a significant role in settling the population in rural areas and reducing social inequalities, especially in locations where agriculture and formal employment are the main sources of livelihood (Ferreira, 2021).

Rural development through tourism is widely recognized as a strategy to diversify the economy in the countryside. This process includes introducing new products and services in emerging markets, promoting a multifaceted and multi-determined approach. According to Kageyama (2004), practices such as landscape management, environmental conservation, agritourism, organic agriculture, the production of regional specialties and direct sales are examples of initiatives that are significant for the complexity of rural development. In addition, rural development establishes a new paradigm by creating new products and services for new markets, with different objectives, such as the production of public goods; generation of complementary income for the owner; preservation and conservation of natural, cultural and historical heritage; appreciation of culture and regionalism; integration of visitors with local history; the search for synergies with local ecosystems; the economy of scale with the pluriactivity of rural households (Azevedo, & Rodrigues, 2015; Blanco, 2004; Caliari et al., 2016; Cipolat et al., 2019; Dias, 2003; Machado, 2005; Ploeg, 2008).

Among the activities that contribute to sustainable socioeconomic development, tourism stands out as a relevant strategy. According to the Ministry of Tourism (Brasil, 2015), several actions are important to promote the sustainable development of tourism. Among these initiatives, the following stand out: a) the integration of local production into the tourism production chain, with actions aimed at promotion and marketing, supporting projects that ensure the sustainability of tourism activities at the local level; b) the encouragement of community-based tourism, through support for projects and actions that favor sustainable development, with a focus on the organization and qualification of production, the improvement of services and the encouragement of associativism, cooperativism and entrepreneurship; and c) the induction of tourism in priority areas for investment, with positive socioeconomic impacts, especially in territories with low Human Development Indexes (HDI), contributing to local development and job creation. In a complementary way, according to Bosetti and Oliveira (2016, p. 43), tourism is currently perceived as an innovation aimed at the socioeconomic development of locations that seek to raise the quality of life of their inhabitants. According to the available attractions, many municipalities invest in the tourism sector in order to reduce unemployment, increase income and mitigate the social exclusion of the most vulnerable groups, such as women and young people who often face the absence of social opportunities. Recent research highlights the inclusive potential of rural tourism, especially for women and young people, given that the activities developed, such as artisanal production, accommodation services, gastronomy, and acting as cultural guides, favor the insertion of these groups in the labor market, promoting autonomy and sustainability (Oliveira and Santos, 2022).

In this study, a qualitative approach was chosen, with the purpose of analyzing the empirical and subjective elements related to the mapping of potential rural enterprises through rural tourism, being a fundamental step to understand the economic, social and cultural dynamics involved. This technique consists of choosing problem situations and aims to promote a consolidated discussion on theoretical foundations, in addition to presenting strategies adopted in reality, which can serve as a model for other communities that have experienced the same circumstances (RICHARDSON, 2012).

The approach of this project aims to capture the richness of rural women's and youth's experiences and perceptions of rural entrepreneurship and tourism, ensuring a holistic understanding that goes beyond numbers, and thus providing valuable input for the development of effective empowerment strategies and fostering inclusive rural enterprises.

The present study worked with primary and secondary data. The primary data were collected based on field research, carried out through 50 semi-structured interviews with women of all ages and young people up to 30 years old, using a questionnaire to map aspirations, perceived challenges and existing skills, considering aspects such as economic options, development and inclusion. Secondary data were extracted from public sources such as databases, including the IBGE, as well as articles, books, magazines, theses and dissertations, enabling an in-depth review of the literature on rural entrepreneurship, rural tourism, rural development, gender equality and youth empowerment.

The analysis of the qualitative data, from the open questions of the interviews, was carried out based on content analysis, according to the method proposed by Bardin (2011), complementing the answers to the guiding questions of the study. Quantitative data, such as family income and migration indexes, were analyzed using descriptive statistics using Excel software.

The data obtained show that most of the interviewees are in the age group between 30 and 50 years old, although a significant portion of young women, aged between 18 and 30 years, are also present. These results showed that, among the women participating in the research, most belong to more advanced age groups, demonstrating that the field has been undergoing an aging process. Comparatively, the demographic data obtained by the 2000 and 2010 Censuses show a decrease of 2 million people living in rural areas, of which 50% are young people aged between 15 and 29 years. This indicates that, of the Brazilians who migrate to the cities, the vast majority are young people who find themselves without prospects of income and quality of life in the countryside. Thus, it is possible to state that the rural exodus is predominantly composed of young individuals (IBGE, 2018).

About 46% of the interviewees live in Ituiutaba, while 33% live in Capinópolis and the others are distributed among the neighboring municipalities of the region, such as Santa Vitória, Canápolis and Cachoeira Dourada. Regarding the relationship of the interviewees with the rural environment, it is observed that most identify themselves as children of farmers. Next, rural workers stand out, followed by landowners. The other interviewees belong to the group of tenants. This panorama is in line with data from the 2017 Agricultural Census, which shows that 20.1% of the registered production units (1,040,022 out of a total of 5,175,489) are not managed by owners, but by tenants, partners, occupants and producers without area.

Regarding the main activities developed on the properties, agricultural activity stands out as the most predominant, followed by dairy farming and beef cattle. This scenario is due to the fact that sugarcane has become the main agricultural crop in Ituiutaba, especially after the installation of mills in the region, because before the growth of sugarcane, livestock was the predominant activity. As for the monthly income obtained on the properties, 74% of the interviewees reported that it comes exclusively from activities developed in the rural area, while 26% of the interviewees indicated that it also includes services provided in the urban area. The predominance of income from rural activities highlights the relevance of the agricultural sector in the local economy.

The results obtained indicate that rural tourism can be considered a viable practice for the region of Ituiutaba, especially if driven by the creation of tourist itineraries that highlight the local culture and the environment. Only 10% of respondents reported knowing what rural tourism is and tried to implement it on the property. This is often due to the fact that the concept is unfamiliar, as many people still do not have a clear understanding of what rural tourism involves. In addition, inadequate promotion of rural tourism opportunities can contribute to a lack of knowledge. Many rural initiatives lack effective marketing and visibility, causing potential visitors and even residents themselves to not recognize the available offers. In this sense, more accessible and educational information could help increase awareness and interest in this practice.

Regarding the cultural aspects on the properties, approximately 16% of the interviewees reported that they have already had or still have cultural practices such as religious festivals, music festivals, farms for events, bullfighting, sport fishing and even soccer. A relevant fact for the survey is that 90% of respondents have never carried out or thought about any type of market research to assess the probability of rural tourism on their property, only 10% did. This scenario highlights an important gap, as market research is an essential tool for understanding consumer behavior, identifying industry trends, and exploring growth opportunities. The absence of this practice can limit the development of rural tourism, preventing owners from adjusting their offers to real demands and maximizing the economic potential of the activity.

With regard to the production of homemade food or the manufacture of handicrafts by the interviewees, the data revealed that 66% did not develop these activities. This result is worrying in the context of rural tourism, since these practices, especially if developed by women, play a crucial role in preserving cultural identity, valuing traditional knowledge, and generating symbolic value, going beyond contributions of an economic nature (LIMA et al., 2023). In addition, and in agreement with Brenzan et al (2021), tourism can awaken the female entrepreneurial side, which once again emphasizes the versatility of women who can perform management activities that go beyond managing domestic tasks. The options most frequently selected by respondents for implementing a rural tourism project on their properties were, firstly, horseback riding, followed by motorcycle trails and catch and pay. The other alternatives mentioned include picnics, sport fishing, accommodation in farm hotels, rural routes, among others. The diversification of activities offered in rural tourism is essential to attract different tourist profiles and promote the sustainable development of local communities.

Among the adversities raised for the implementation of rural enterprises are the financial challenges and the limitations of the options available on the property, followed by a lack of specialized knowledge and fear of failure of the enterprise. Many also highlighted the absence of external public policies to strengthen tourism infrastructure and facilitate access to credit. These aspects highlight the need for articulation between the public and private sectors, with the objective of fostering the expansion and qualification of rural tourism in a sustainable and inclusive manner. It is important to note that there are national public policies that encourage sustainable rural tourism in family farming, such as: the National Program for the Strengthening of Family Farming – PRONAF, which grants financing with interest rates lower than the market rates, and the National Program for Rural Tourism in Family Farming – PNTRAF, which encourages the development of tourism activities through collaboration between government organizations, technicians and family farmers, promoting national integration and the strengthening of local networks. However, despite the existence of initiatives, misinformation and lack of adequate dissemination by the competent bodies often result in limited implementation, without the expected effectiveness.

About 30% of the young people showed interest in tourism activities and reported that, if there were technical courses and training with local institutions, they would be interested in developing skills in management and customer service. These data corroborate previous studies, such as that of Almeida and Santos (2020), which point to rural tourism as a tool for emancipating and retaining the young population in the countryside, through the development of entrepreneurial skills, appreciation of local culture, and strengthening of rural identity. In addition, the participation of young people in rural tourism contributes to the revitalization of rural areas, promoting innovation and continuity of local traditions. In accordance with Gaweleta and Billota (2022), it is highlighted that by getting involved in tourism activities, young people introduce new perspectives and technologies (disclosures on social networks, forms with suggestions for improvements, scheduling visits and purchases of products online, digital maps, among others), attracting visitors of different age groups and diversifying family income sources. Rural tourism becomes an opportunity to develop a business for these young people, since when well structured, tourism ceases to act as a complementary activity and assumes the role of the main economic activity, since in the properties studied the main economic activities are concentrated in traditional activities such as livestock and agriculture. In this same perspective, studies indicate that rural tourism contributes to the sustainable development of rural communities, by integrating young people in initiatives that preserve the natural and cultural heritage and that enable them to lead socioeconomic transformations in their own regions (Gavira; Menasche, 2006). As pointed out by Araújo et al. (2013), in Brazil, professional qualification in the rural tourism sector still faces significant challenges, even in the face of its high potential to contribute to the rural economy and promote sustainable development. Despite the country's vast cultural and natural wealth, training programs are not always adequate to the specificities of the sector. Issues such as the management of rural enterprises, customer service and sustainable practices often need attention, which compromises the full use of the opportunities offered by rural tourism.

In terms of evaluating the rural tourism activities currently present in the interviewee's municipality, they demonstrate a heterogeneous distribution of the answers, with a greater concentration on values 0, 4, and 6, representing respectively 16%, 16%, and 14% of the respondents' opinions. The predominance of medium and low grades suggests that rural tourism activities in the region are perceived as insufficiently designed or exploited, reflecting a significant gap in the exploitation of existing rural potential. This result can be interpreted as an indication of the need for greater investment in infrastructure, marketing and technical training to make rural tourism a more expressive and attractive activity for tourists and local residents.

92% of participants believe that social media plays a significant role in promoting rural tourism. Only 2% stated that they did not consider the use of social networks relevant for this purpose, while 6% were indifferent, which suggests the need to raise awareness about the efficient use of these tools. These results highlight the importance of digital platforms as strategic tools for the dissemination and appreciation of rural tourism, especially among women and young people, audiences that are often more engaged in the use of these technologies. Social networks can act as mediators in creating connections between rural entrepreneurs and tourism potentials, promoting the reach of wider and more diversified markets.

3 FINAL CONSIDERATIONS

The general objective of the research was to demonstrate the importance of rural tourism as an instrument for local development and social inclusion for women and young people in Ituiutaba-MG. In addition, the mapping of potential rural enterprises emerges as an innovative and essential strategy, aimed at the economic and social empowerment of women and young people who live in rural areas. When properly planned and structured, it attracts investment and development to local communities by ceasing to act as a complementary activity, transforming the reality of the place and causing positive impacts, such as valuing local culture and strengthening rural identity.

The research showed that rural tourism presents itself as a viable alternative to promote the economic engagement of women and young people, contributing to income generation, reducing dependence on large urban centers and strengthening the local social fabric. Although initiatives related to rural tourism have great potential, their full development depends on the improvement of public policies and training strategies. Such measures are essential to ensure the sustainable growth of the activity and the generation of long-term benefits for the communities involved.

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MANAGEMENT OF SCALE INSECTS IN ACEROLA ORCHARDS IN THE BRAZILIAN ACEROLA BELT

MANEJO DE COCHONILHAS DA ACEROLEIRA NO CINTURÃO ACEROLEIRO BRASILEIRO

MANEJO DE COCHINILLAS DE LA ACEROLA EN EL CINTURÓN ACEROLERO BRASILEÑO

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ABSTRACT
The Brazilian acerola belt, composed of production hubs in the Northeast, forms the main global acerola production region. In Northeast Brazil, acerola trees have adapted better to edaphoclimatic conditions; farms operate production systems with higher technological levels and maturity, and there is infrastructure for agro-industrial processing. One of the factors that compromise acerola production is infestation by scale insects (Hemiptera: Sternorrhyncha: Coccomorpha). Nymphs and adult females cause injury and damage through stylet insertion, continuous sap sucking, and injection of toxic saliva during feeding. The management of scale insects represents a critical factor, as these pests can cause financial losses by reducing productivity and increasing production costs. In this context, this chapter aims to synthesize current scientific information on scale insects associated with acerola, with particular emphasis on their management in acerola cultivation within the Brazilian acerola belt.

Keywords: Fruit Growing. Pests. Hemiptera.

RESUMO
O cinturão aceroleiro brasileiro, constituído pelos polos de produção do Nordeste, formam o principal cinturão de produção mundial. No Nordeste do Brasil a aceroleira se adaptou melhor às condições edafoclimáticas, as propriedades possuem sistema de produção com maior nível e maturidade tecnológica e encontra-se infraestrutura para o processamento agroindustrial. Um dos fatores que comprometem a produção da aceroleira é a infestação por cochonilhas (Hemiptera: Sternorryncha: Coccomorpha). As ninfas e fêmeas adultas ocasionam injúria e dano a partir da introdução do estilete, sucção contínua de seiva e injeção de saliva tóxica durante a alimentação. O manejo de cochonilhas representa um fator crítico, as cochonilhas podem ocasionar prejuízo financeiro com a redução da produtividade e aumento do custo de produção. Nesse contexto, com o presente capítulo buscou-se sintetizar as informações científicas atuais sobre as cochonilhas associadas à aceroleira,

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discutindo particularmente sobre o manejo de cochonilhas no cultivo da aceroleira no cinturão aceroleiro brasileiro.

Palavras-chave: Fruticultura. Pragas. Hemiptera.

RESUMEN

El cinturón aceroleiro brasileño, constituido por los polos de producción del Nordeste, conforma la principal región productora de acerola a nivel mundial. En el Nordeste de Brasil, la acerola se ha adaptado mejor a las condiciones edafoclimáticas; las propiedades cuentan con sistemas de producción con mayor nivel y madurez tecnológica, y existe infraestructura para el procesamiento agroindustrial. Uno de los factores que comprometen la producción de la acerola es la infestación por cochinillas (Hemiptera: Sternorrhyncha: Coccomorpha). Las ninfas y las hembras adultas ocasionan lesiones y daños mediante la introducción del estilete, la succión continua de savia y la inyección de saliva tóxica durante la alimentación. El manejo de cochinillas representa un factor crítico, ya que estas plagas pueden ocasionar pérdidas económicas debido a la reducción de la productividad y al aumento de los costos de producción. En este contexto, el presente capítulo tuvo como objetivo sintetizar la información científica actual sobre las cochinillas asociadas a la acerola, abordando particularmente su manejo en el cultivo de la acerola en el cinturón aceroleiro brasileño.

Keywords: Fruticultura. Plagas. Hemiptera.

1 INTRODUCTION

Acerola is the common name of *Malpighia emarginata* DC (Magnoliopsida: Malpighiaceae), a fruit tree found naturally in tropical and subtropical America, whose temperature demand varies between 15 and 32 °C (Assis et al., 2008; Calgaro; Braga, 2012). This name also applies to *Malpighia glabra* L. (= *Malpighia punicifolia* L.), a fruit tree with small, tasteless fruits and low juice production (Ritzinger, Ritzinger, 2011). The widely cultivated species (i.e., *M. emarginata*) is a shrub up to 3 m tall, with dense and scattered branches, opposite leaves, inflorescence with 3 to 5 perfect flowers and rounded, oval or conical fruits of red, purple, yellow or white color when ripe (Calgaro; Braga, 2012).

Acerola was disseminated after the discovery of the high content of ascorbic acid in fruits (Calgaro; Braga, 2012), which also have phenolic compounds, carotenoids, anthocyanins and antioxidant power (Mariano-Nasser et al., 2017; Prakash; Baskaran, 2018). Fruits and by-products are relevant in human and animal food and pharmacology (Almeida et al., 2014; Corrêa et al., 2017; Reis et al., 2017; Milindro et al., 2019). The fruit is climacteric, develops and matures in about 21 days, providing several harvests and short time for commercialization (Ritzinger et al., 2018). The fruit is harvested green for the vitamin supplement industry or ripe (beginning of ripeness) when destined for fresh consumption or juice and pulp industry.

The acerola tree has been cultivated in Brazil, Mexico, India, and Southeast Asia (Duke; Ducellier, 1993; Rezende et al., 2017). It was introduced in Brazil by multiple incursions throughout the nineteenth and twentieth centuries (Soares Filho; Oliveira, 2003; Calgaro; Braga, 2012). Initially it was introduced without commercial appeal, later the cultivation prospered due to its nutritional relevance. The first commercial orchards were established in the State of Pernambuco in 1955, marking the establishment of the species as cultivated in Brazil (Ritzinger; Ritzinger, 2011), recognized as an introduced cultivated species by ordinance No. 221 of September 12, 2018 (MAPA, 2018). Brazil has become the largest producer, consumer and exporter of acerola (IBGE, 2017).

The productive poles of the Northeast named here as Baixo Parnaíba (Parnaíba, Tianguá and Ubajara), Norte Cearense (Maranguape and Baturité), Submédio valley of the São Francisco River (Petrolina, Casa Nova, Juazeiro and Sobradinho), Baixo valley of the São Francisco River and adjacent municipalities (Coruripe, Lagarto, Poço Redondo and Penedo) and Zona da Mata (Alhandra, Pitimbu, Moreno, Pombos, Conde and Vitória de Santo Antão) form the main world production belt (i.e., the Brazilian acerologer belt) covering the states of Piauí, Ceará, Rio Grande Norte, Paraíba, Pernambuco, Alagoas, Sergipe and Bahia. Where the acerola tree has adapted better to the edaphoclimatic conditions, the properties have a production system with a higher level and technological maturity and there is infrastructure for agro-industrial processing.

Several species of insects have been associated with acerola, which can cause a relevant reduction in fruit quality and productivity. Acerola insects are phytophagous, entomophagous (predators and parasitoids), pollinators, trophobions, and pillages. The phytophagous insect guild is composed of hemiptera, coleoptera, diptera and hymenoptera, with particular relevance as a pest for hemiptera (Albuquerque et al., 2002; Ritzinger et al., 2018).

The order Hemiptera is the most diverse among hemimetabolous insects, about 106 thousand species belonging to the suborders Heteroptera (about 45 thousand), Auchenorrhyncha (about 43 thousand), Sternorryncha (about 18 thousand) and Coleorrhyncha (37 species) are known (Grazia et al., 2024). The mealybug complex (Hemiptera: Sternorryncha: Coccomorpha) brings together the main pests of acerola, particularly in the Northeast production belt.

Mealybugs are the morphologically most specialized members of the order Hemiptera, forming a monophyletic group within the suborder Sternorrhyncha, with tarsal monomers and a single claw, the remaining sternorrhynchus have two tarsal claws (Hodgson et al., 2021; Wolff et al., 2024). Within the Infraorder Coccomorpha, 56 families are currently recognized (36 current and 20 extinct) (Wolff et al., 2024).

Currently, about 559 species are known distributed in 20 families in Brazil (Grazia et al., 2024). Mealybugs are insects that infest a wide range of economically exploited hosts, including acerola (Ramos et al., 2018). Here, we synthesize the current scientific information on mealybugs associated with acerola, particularly discussing the management of mealybugs in the cultivation of acerola in the Brazilian acerola belt.

2 CATALOGED RECORD OF MEALYBUGS ASSOCIATED WITH ACEROLA.

In the "*ScaleNet*" *database* there are about 27 species of mealybugs associated with plants of the genus *Malpighia* L., several species are associated with *M. glabra* (García Morales et al., 2016). Currently there are 18 species belonging to six zoological families associated with the M acerola tree. *emarginata*, mainly in countries or territories of the American continent (Table 1). In Brazil, 12 species from five zoological families (i.e., Coccidae, Diaspididae, Monophlebidae, Ortheziidae and Pseudococcidae) were found to be associated with acerola (Table 1).

The Coccidae family includes the soft mealybugs, currently 1,223 species are known distributed in 177 genera (Garcia Morales et al., 2016). In Brazil, 156 species are known in 43 genera (Grazia et al., 2024). In the acerola tree, species belonging to the subfamily Pulvinariscinae and to the genera *Saissetia* Deplanche and *Coccus* Linnaeus have already been recorded. The genus *Saissetia* has 46 valid species (García Morales et al. 2016), among which *Saissetia coffeae* (Walker) and *Saissetia oleae* (Olivier) have already been recorded in acerola in the municipality of Angulo – PR (Albuquerque et al., 2002). The genus *Coccus* has 114 valid species, among which *Coccus viridis* (Green) has already been recorded in acerola in the municipality of Angulo – PR (Albuquerque et al., 2002) and *Coccus hesperidium* (Linnaeus) has already been recorded in acerola in Paço do Lumiar – MA (Ramos et al., 2018). In the chapter "Pests of acerola tree", published in the book "Pests of tropical fruit trees of agro-industrial importance", in 1998, the authors refer to *the species C. viridis* and *C. hesperidum* as a pest of acerola and mention its occurrence in Brazil (Sobrinho et al., 1998).

Table 1

Records of infestation by mealybugs in the acerola tree

Taxonomic identification	Geographic region		Source
Species2	Country	State1	
Cerococcus deklei	Cuba	-	Fernández et al., 2021
Ceroplastes cirripediformis	France	French Antilles	Matile-Ferrero and Étienne, 2006
Pulvinaria urbicola	Japan	Ryukyu Islands	Tanaka and Kamitani, 2020
Saissetia coffeae	Brazil	Paraná	Albuquerque et al., 2002
Saissetia oleae	Brazil	Paraná	Albuquerque et al., 2002
Coccus viridis	Brazil	Paraná	Albuquerque et al., 2002

Coccus hesperidum hesperidum	Brazil	Maranhão	Ramos et al., 2018
Chrysomphalus aonidum	Brazil	Paraná	Albuquerque et al., 2002
Selenaspidus articulatus	Brazil	Paraná	Albuquerque et al., 2002
Icerya purchase	Brazil	-	Sobrinho et al., 1998
	USA	Hawaii	Hale et al 1970
Crypticerya zeteki	Brazil	Maranhão	Ramos et al., 2018
Insignorthezia insignis	Brazil	Ceará	Ponte et al., 2004
Praelongorthezia praelonga	Brazil	Paraná	Albuquerque et al., 2002
		Pernambuco	Barbosa et al., 2007
		Bahia	Nascimento; Habibe, 2009
Spilococcus mamillariae	France	French Antilles	Matile-Ferrero and Étienne, 2006
Paracoccus marginatus	India	Tamil Nadu	Sakthivel et al 2012
Maconellicoccus hirsutus	Brazil	Maranhão	Ramos et al., 2018
	Brazil	Alagoas	Broglio et al., 2015
Planococcus lilacinus	-	-	García Morales et al., 2016
Dysmicoccus brevipes	Brazil	Pernambuco	Sá e Oliveira, 2021

[1]State, province or territory. 2Scientific names according to García Morales et al., 2016.
Source: compiled and prepared by the authors.

Diaspididae is the largest family of coccids, with 2,696 species distributed in 417 genera (García Morales et al., 2016). They are known as shielded or carapace mealybugs because their body is covered by a detachable waxy secretion (Grazia et al., 2024). Only the species *Chrysomphalus aonidum* (L.) and *Selenaspidus articulatus* (Morgan) were recorded in the acerola tree in the municipality of Angulo, PR (Albuquerque et al., 2002). Both are polyphagous and cosmopolitan, registered in all continents and several states of Brazil

(García Morales et al., 2016). *Chrysomphalus aonidum* has been associated with plants of 181 genera in 74 botanical families in 87 countries and *S*. *articulatus* has been associated with 105 genera in 53 botanical families in 62 countries (García Morales et al., 2016).

The Monophlebidae family has 265 species distributed in 48 genera (García Morales et al., 2016), in Brazil there are 17 species distributed in nine genera (Grazia et al., 2024). They are known as giant mealybugs, 35 mm long, usually oval (Grazia et al., 2024). The species *Icerya purchasi* Maskell and *Crypticerya zeteki* Cockerell have already been recorded in acerola in Brazil (Sobrinho et al., 1998; Ramos et al., 2018).

The Ortheziidae family has 214 species distributed in 24 genera (García Morales et al., 2016), in Brazil 13 species have already been recorded in seven genera (Silva et al., 1968; Bem-Dov et al., 2011). They are covered by wax arranged in the form of plates, on the dorsum and marginally (Grazia et al., 2024). In the Ortheziidae family, the species *Insignorthezia insignis* Browne and *Praelongorthezia praelonga* (Douglas) (Hemiptera: Ortheziidae) have already been recorded in acerola in Brazil (Albuquerque et al., 2002; Ponte et al., 2004; Barbosa et al., 2007; Nascimento; Habibe, 2009).

The Pseudococcidae family has 2,042 species distributed in 259 genera (García Morales et al., 2016), in Brazil more than 96 species have been recorded in about 22 genera (Grazia et al., 2024). They are called "mealybugs" because adult females have their bodies covered with whitish powdery wax (Grazia et al., 2024). The species *Spilococcus mamillariae* (Bouche*), Paracoccus marginatus* Williams & Willink's granara, *Maconellicoccus hirsutus* **(**Green), *Planococcus lilacinus* (Cockerell) and *Dysmicoccus brevipes* (Cockerell) have already been recorded in acerola (Table 1). In Brazil, the species *M*. *hirsutus* and *D*. *brevipes* were found infesting acerola in the Northeast region (Broglio et al., 2015; Ramos et al., 2018; Sá and Oliveira, 2021).

3 RECOGNITION OF THE KEY PEST(S)

The mealybugs associated with acerola on planet earth (18), Brazil (12) and Northeast (six) were summarized in Table 1. Only three species were associated with acerola in the Brazilian semi-arid region: *P*. *praelonga* (Barbosa et al., 2007; Nascimento; Habibe, 2009), *I. insignis* (Ponte et al., 2004) and *D. brevipes* (Sá; Oliveira, 2021). The productive poles of the acerola belt are predominantly located in the semi-arid region, however, the scarce scientific records do not translate the importance of mealybugs as an agricultural pest in the acerola belt, it only identifies the need for scientific research.

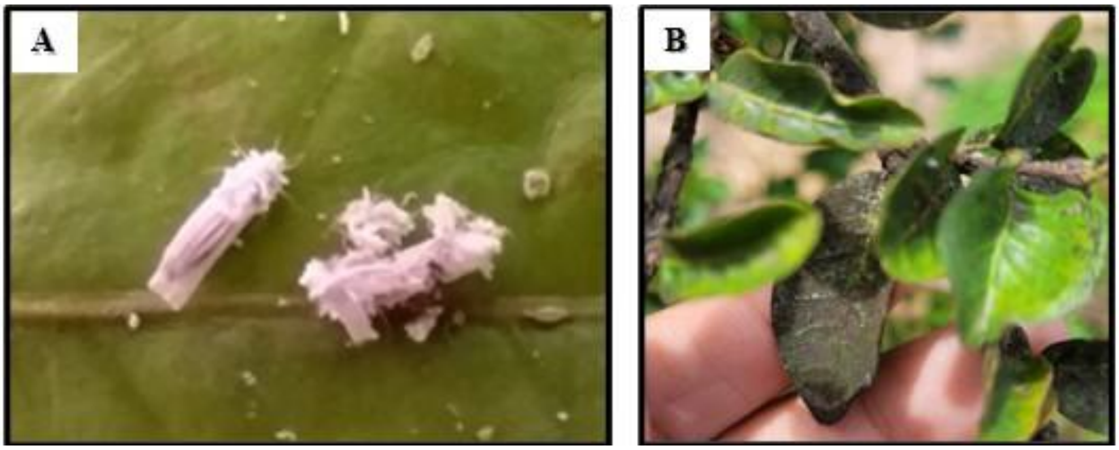
The ortézia is the main species found in the acerola tree, and it also represents the cochineal with the largest number of scientific records (Table 1). To date, the ortézia is the only one that can be considered a key pest. Secondary pests are found to be the brown mealybug, *C. hesperidium*, green mealybug, *C. viridis* the white aphid, *I. purchasi*, and the Hibiscus Pink Mealybug, *M. hirsutus*. The latter has been an emerging problem, it is a polyphagous cochineal that feeds on plants of 259 genera and 84 botanical families and registered in 110 countries (Garcia Morales et al., 2016). The first record in Brazil occurred in 2010 in the State of Roraima (Marsaro Júnior et al., 2013), shortly thereafter it was detected in Espírito Santo (Culik et al., 2013), Mato Grosso (Morais et al., 2015), Alagoas (Broglio et al., 2015), Bahia (CEPLAC/CEPEC, 2014) and Santa Catarina (Alexandre et al., 2014). For the other species cataloged, there are no widely known records of outbreaks and losses in acerola orchards.

As general characteristics, mealybugs have a body with variable shape and color and length between 0.5 and 35 mm, with a waxy coating or covered by lacquer with a characteristic composition and structure that determine the separation of many families (Cruz, 2018). Adult females are always apterous and neotenic, reaching the adult stage after two or three instars and have a completely fused head, thorax and abdomen; with developed appendices, or they may still be apodated and have reduced numbers of antennal segments in some families (Cruz, 2018). Unlike females, adult males are winged, have a division of the body into head, thorax and abdomen, in addition to having their mouthparts atrophied and passing through two or three mobile nymphal instars and one or two pupals (prepupae and pupa) (Cruz, 2018).

The key pest Orthozia is easily recognized in the field, males and females have characteristic sexual dimorphism. Females are apterous, neotenic (with morphological characteristics of nymphs), white (their bodies are covered by waxy white plaques), devoid of chitinous carapace, and have a completely fused head, thorax, and abdomen. In the posterior part of the females' body, the ovisack (elongated tail covered by waxy plaques) develops, where the eggs are deposited. The ovisack protects the eggs and ensures the hatching and protection of the nymphs until the first ecdysis, favoring the gradual displacement of the nymphs to the plant structures (Figure 1A).

Figure 1

Ortézia in acerola. (A) Female; (B) Sooty mold on the leaf surface



Source: prepared by the authors.

The nymphs of males and females are the same, however, in the second instar the males move to the trunk where they group and transform into pseudopupa until they reach the adult stage. Males are winged, bluish and have tails with elongated white bristles.

4 BIOECOLOGY, DAMAGE AND LOSS.

Bioecological and behavioral aspects determine the spatial distribution, fluctuation and infestation of mealybugs in the field. Mealybugs have a fast biological cycle and a high capacity to generate offspring (Cruz, 2018). In the acerola orchard, initially the mealybugs have a heterogeneous and localized distribution (i.e., in a reboleira), mainly because the females are apterous. Some plants may present infestation while in others the pest is not detected, with the advance of the infestation the mealybugs can spread throughout the plot or orchard. The infestation initially occurs in the internal shoots and basal branches, making early diagnosis difficult. Detection is facilitated with the multiplication of mealybugs and the development of sooty mold (Benvenga et al., 2001).

The mealybugs disperse using the wind as a vehicle for natural dissemination between plants, plots, orchards and between orchards, providing primary and secondary infestation. Dispersion can also occur by walking itself, through infested seedlings and mechanically when provided by man, machinery and equipment in the various operations (i.e., harvesting, cultural treatments, irrigation, fertilization and phytosanitary management). There are also species of ants (Hymenoptera: Formicidae) that provide protection and dispersion of ants to maximize the production of *honeydew*, secretion of mealybugs used for food by ants.

The cochineal ortézia *P. Praelonga* easily dispersed in the acerola production environment, the absence of chitinous carapace provides high mobility in the plant in the nymph and adult stages, facilitating its natural dissemination by the wind. The waxy coating of the body favors mechanical dissemination over short and long distances due to the insect's adherence to humans (e.g., clothing), machinery and equipment. Orcezia polyphagia also favors dispersal in the orchard environment, since other host plants can act as green bridges providing shelter, feeding, multiplication and consequent dispersion and reinfestation of the orchard by the orthezia.

Mealybugs can be found during all months of the year, however, they are favored by high temperatures and low relative humidity. The greatest infestations occur in the dry season, a period with rainfall lower than evapotranspiration and lower relative humidity of the air. As a hypothesis, it is suggested that in the dry period there is a higher concentration of nutrients in the sap of acerola trees, favoring the development and reproduction of sucking insects. In addition, the dry period usually restricts the development of entomopathogens, reducing the natural mortality of mealybugs.

The dry season in the Brazilian acerola belt lasts for up to eight months, which favors the multiplication of mealybugs. The semi-arid Northeast presents marked interannual variability of precipitation with some rainy or dry years, and even drier years may occur. Dry years result in greater damage caused by mealybugs in acerola trees, resulting in crop failure. In addition, the mealybug population can increase exponentially in the rainy season due to the occurrence of veranicos (consecutive days with no precipitation).

Mealybugs can be found in practically all plant structures, including leaves, shoots, branches, trunks, flowers and fruits (Sobrinho et al., 1998; Broglio et al., 2015; Ramos et al., 2018; Cruz, 2018). In the acerola tree, mealybugs form colonies with numerous specimens, in addition, they have overlapping generations with all stages of development.

The damage is caused by nymphs and adult females, adult males do not cause damage to the plant since they have an exclusive function of reproduction. The nymphs and females cause injury and damage from the introduction of the stylet, continuous suction of sap and injection of toxic saliva during feeding, culminating in malformation of shoots, leaves, branches, stems, flowers and fruits.

Mealybugs occur from the molting stage, the earlier the infestation, the greater the effect on the development and formation of the acerola tree. The damage caused depends on the population density of the pest and the stage of development, vigor, nutrition and water supply of the acerola tree. Mealybugs can cause growth retardation, decline and death of seedlings and newly transplanted plants in the first two years. The infested adult plant withers, with drying of the branches and premature fall of leaves and fruits (Barbosa et al., 2007). The infestation reduces the productivity of the current crop and eventually of the future ones.

Mealybugs have low feed conversion and excrete approximately 90% of the ingested food (i.e., *honeydew*). The fungus (*Canopodium* spp.), precursor of sooty mold *, uses honeydew* for its nutrition and develops superficially in the vegetative shoot (i.e., leaves, branches and eventually fruits), and can propagate throughout the crown of the acerola. The fungus does not infest the plant's tissues, it only covers them with sooty mold, a coating of thick sticky black crust formed by the fungus' black and sooty mycelia (Figure 1B). Sooty mold decreases the photosynthesis, respiration and transpiration of the plant, in addition, it stains the fruit reducing its commercial value (Ramos et al., 2018).

5 INTEGRATED MANAGEMENT OF MEALYBUGS IN ACEROLA ORCHARD.

For phytosanitary management, the rural entrepreneur must consult an Agronomist, a qualified professional for guidance and consulting. The rural entrepreneur must choose to plant certified, healthy and pest-free seedlings, mitigating infestations in the field in the most critical period (i.e., establishment of the crop). Control must be strict to prevent seedlings from constituting an initial source of infestation in the field. In the seedling production phase, the relevant pests are sucking insects (i.e., mealybugs and aphids).

The seedling nursery (i.e., greenhouse or greenhouse) should contain an antechamber and insect screen to mitigate the entry of mealybugs and aphids. In infestations in the nursery, it is possible to adopt simple curative measures depending on the number of seedlings. Insect vacuums are practical for collecting and removing nymphs and adult females from mealybugs, in addition, it is possible to carry out manual scavenging and crushing, mealybugs in these biological phases are apterous and easy to see and collect. It is also possible to clean the infested parts with water jets, brushes or other equipment, the application of water with the addition of detergent/soap can increase the effectiveness of control causing removal, anoxia and/or dehydration due to the removal of the wax layer from the cuticle of the integument by lauric acid.

Oils (mineral and vegetable) and phytoprotective mixtures (i.e., soap, lime sulfo, and Bordeaux) can be sprayed on seedlings for curative control of mealybugs in the nursery. Details about the mixtures can be found in the agroecological files of the Ministry of

Agriculture, Livestock and Supply - MAPA. As a last resort, pesticides registered in MAPA should be applied for acerola. The active ingredient flupyradifurone of the chemical group butenolide is the only active ingredient with a commercial formulation registered in Brazil for the acerola crop for the curative control of the key pest *P*. *praelonga* and the secondary pests of the genus *Saissetia* and *Icerya*. The pesticide can be used in the seedling nursery and in the field as discussed below (Table 2).

Table 2

Mealybug management techniques in the production of acerola seedlings

Control	Management technique
Preventive	Protected cultivation adopting a greenhouse with antechamber and protective screen against mealybugs.
Dressing	Aspiration of mealybugs.
	Manual picking and crushing.
	Mechanical control with application of soapy water flow.
	Application of mixtures (calcium and Bordeaux sulfo).
	Spraying mineral or vegetable oils.
	Spraying of insecticide with active ingredient flupyradifurone.

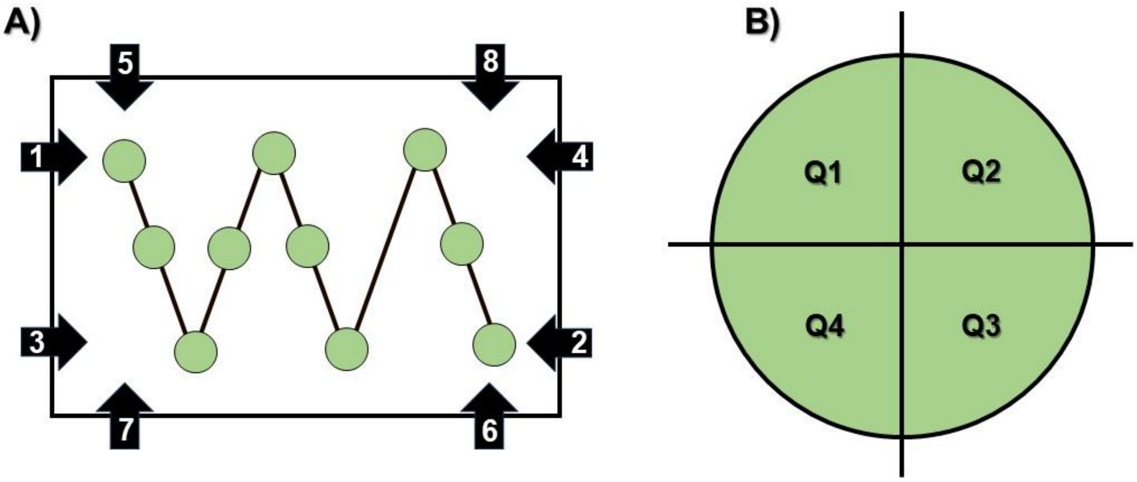
Source: prepared by the authors.

Field monitoring aims to detect the presence and establish the history of occurrence of mealybugs on the property, reducing costs and losses. The diagnosis of mealybugs should be carried out during the day, weekly and systematically through active inspection of the occurrence of nymphs and adult females. In the monitoring, at least one percent of the plants in the cultivated area (plot) must be inspected in a randomized manner in a zigzag path (Figure 2A). In an area of one hectare with 1,000 plants, it is recommended to examine at least 10 plants. At each sampling point, the plant should be divided into quadrants and one branch per quadrant should be examined, totaling four branches per plant (Figure 2B). The inspector should observe the underside of the leaves and branches to check for the presence of mealybugs and sooty mold, in addition, the trunks of the plants should also be inspected. The plant should be considered infested when the presence of at least one nymph or adult female is found. The presence of mealybugs associated with sooty mold indicates a higher population density of the pest in the acerola plant and/or orchard.

If mealybugs are detected during monitoring (routine inspection), then a plant-by-plant sweep inspection in the orchard becomes necessary. In this operation, the infested plants will be demarcated and the spatial distribution of the mealybugs will be defined. The ideal time to use curative control is when the initial focus is detected in the field, i.e., when they still have localized (aggregated) distribution. Curative control can be used only in the foci of the infestation, individually in infested plants or in shrubs. Success depends on the early and accurate diagnosis of infested plants and the immediate adoption of curative control, since mealybugs have a high reproduction capacity. In plants with low infestation, visualization can be difficult due to the presence of mealybugs on basal branches, internal leaves and absence of sooty mold. On the other hand, the uniform distribution of mealybugs indicates a high population density of the pest and requires curative treatment in the total area.

Figure 2

Monitoring of mealybugs in the acerola orchard. A) Zigzag walking. B) Quadrants



Source: prepared by the authors.

In the field, planting at the beginning of the rainy season is recommended, since the population of mealybugs is usually lower at this time. Precipitation can remove mealybugs and wash sooty mold from the canopy of the plant, particularly from the leaf surface. Planting in the rainy season linked to proper irrigation management avoids water stress and favors the establishment and rapid development of the acerola tree, minimizing the losses generated by any infestations. It is also necessary to manage nutrition (chemical and/or organic fertilization) according to soil or foliar analysis and crop requirements, avoiding nutrient deficiency and/or excess (Table 3).

To reduce the infestation resulting from the natural spread by the wind, it is recommended to implement live fences (barriers) in the surroundings and crop strips with non-host crops and upright size inside the acerola orchard. To reduce the infestation resulting from mechanical dissemination, it is recommended to restrict the traffic of vehicles and people, as well as the preventive inspection of vehicles, machinery, equipment and people. Protection must be exercised from the external to the internal environment (that is, from the outside to the inside of the property/orchard) and from infested plots to plots free of mealybugs. In the latter case, the movement of people, machinery and equipment in the infested plot should be restricted and the infested plants should be harvested after the end of the other plots free of mealybugs (Table 3).

The plant should be conducted adopting proper pruning management to allow greater luminosity and internal aeration of the canopy. The stages of plant formation consist of the establishment of the seedling, single-stem conduction, definition of the structural branches and budding (for details see Calgaro; Brandão, 2012). The acerola tree produces continuous shoots, making it necessary to carry out periodic cleaning pruning, eliminating thieving and poorly located branches (i.e., branches directed downwards and/or facing the interior of the crown), dry branches and those most infested by mealybugs, which must be burned or buried. Such a measure reduces the proliferation of sooty mold, since the fungus precursor of sooty mold develops better where air circulation is poor and humidity is high. In addition, under these circumstances, mealybugs have a higher energy cost for locating feeding points and shelter in the canopy of the plant, which may increase natural mortality due to the higher rate of encounter with entomophages (predators and parasitoids) and eventual exposure to solar radiation (dehydration). With pruning, the mealybugs also start to be more exposed to possible curative treatments, such as mixtures (soap, calcium sulfur and Bordeaux), oils (mineral and vegetable) and pesticides (Table 3).

To reduce multiplication and secondary dissemination in the orchard, it is recommended to control the host weeds of mealybugs. Weed control should be carried out mainly in the area close to the foci of occurrence of mealybugs, clearing the area at least within a radius of 10 m from the infestation foci (Table 3). The weeds *Emilia sonchifolia (L.) DC.*, *Momordica charantia L.*, *Cyperus rotundus L.* and *Cenchrus echinatus L.* are commonly found in acerola orchards in the semi-arid region (Sousa et al., 2020) and have already been found with *P. praelonga* (Nascimento et al., 1993; Skorupa; Cesnik, 1999), *M. hirsutus* (Lopes et al., 2019) and *D. brevipes* (Lopes et al., 2019).

Table 3

Techniques for managing mealybugs in acerola production in the field

Control	Objective	Management technique
Preventive	Disruption of the synchrony between mealybugs and acerola tree in the field deployment.	Planting in the rainy season.
		Adequate management of irrigation and nutrition aiming at the rapid establishment of the seedling.
	Reduction of the natural spread of mealybugs	Implementation of hedges in the surroundings and crop strips inside the orchard.
		Control of host weeds of mealybugs.
	Reduction of the mechanical spread of mealybugs	Traffic restriction, inspection and cleaning of vehicles, machinery, equipment and people.
		Harvesting in the infested plots last.
	Reduction of favorable microclimate for mealybugs and sooty mold	Execution of pruning providing greater luminosity and aeration of the acerola tree's crown.
Dressing	Population reduction	Application of mixtures (soap, lime sulfo)
		Spraying mineral or vegetable oils.
		Spraying of insecticide with active ingredient flupyradifurone.

Source: prepared by the authors.

As a last resort, the active ingredient flupyradifurone, the only active ingredient with a commercial formulation registered in MAPA for the control of mealybugs in acerola, should be sprayed. The commercial formulation based on flupyradifurone can be applied in the crown of the tree or via "*drench*", the active ingredient can circulate systemically in the acerola tree. The mealybugs are exposed and absorb the insecticidal molecule through contact and/or ingestion, depending on the form of application. Mealybugs are led to death through neuromuscular action in which the active ingredient acts as a competitive modulator of nicotinic acetylcholine receptors (Table 3).

Systemic insecticides are more recommended for the control of sucking insects, in particular for the *P species*. *Praelonga*. Contact insecticides are less effective in controlling the orthezia due to the reduced penetration into the waxy layer that covers the body of this species, in addition, the effect in the initial phases is less due to the females protecting the eggs and nymphs from the first instar in the opossace. The barrier of the waxy layer can be minimized with the use of surfactants in the spray mixture.

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MORPHOMETRIC ANALYSIS AND CARCASS YIELD OF KINOSTERNON SCORPIOIDES (LINNAEUS, 1776) REARED IN CAPTIVITY ON MARAJÓ ISLAND, PARÁ, BRAZIL

ANÁLISE MORFOMÉTRICA E RENDIMENTO DE CARCAÇA DE KINOSTERNON SCORPIOIDES (LINNAEUS, 1776) CRIADOS EM CATIVEIRO NA ILHA DE MARAJÓ-PA

ANÁLISIS MORFOMÉTRICO Y RENDIMIENTO DE CANAL DE KINOSTERNON SCORPIOIDES (LINNAEUS, 1776) CRIADOS EN CAUTIVERIO EN LA ISLA DE MARAJÓ, PARÁ, BRASIL

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ABSTRACT
Muçuã (Kinosternon scorpioides) has economic and social importance in the Amazon region, being widely consumed by the local population. This study aimed to evaluate the morphometry and carcass yield of muçuãs raised in captivity on Marajó Island, Pará, Brazil. A total of 26 (twenty-six) adult female specimens, four years old, from an authorized breeding facility were used. Morphometric analyses included measurements of the carapace and plastron. For yield evaluation, live weight and the yields of meat, viscera, and carcass were determined. The muçuãs showed a mean carapace length of 15.1 ± 0.7 cm and a mean meat weight of 54.5 ± 10.8 g. The mean carcass yield was 19.1 ± 2.8%, which is lower than values reported in the literature. The observed differences were attributed to methodological and biological factors, such as age, genetics, and rearing conditions. It is concluded that muçuãs

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present a morphometric profile consistent with the literature and a carcass yield that is relevant for sustainable production systems in the Amazon.

Keywords: Chelonians. Meat Yield. Chelonian Size.

RESUMO
O muçuã (Kinosternon scorpioides) possui importância econômica e social na Amazônia, sendo amplamente consumido pela população local. Este estudo objetivou avaliar a morfometria e o rendimento de carcaça de muçuãs criados em cativeiro na Ilha de Marajó, Pará. Foram utilizados 26 (vinte e seis) exemplares de fêmeas adultas, com quatro anos de idade, provenientes de criação autorizada. As análises morfométricas incluíram medidas da carapaça e do plastrão. Para o rendimento, os animais tiveram o peso vivo e os rendimentos de carne, vísceras e carcaça determinados. Os muçuãs apresentaram comprimento médio de carapaça de 15,1 ± 0,7 cm e peso médio de carne de 54,5 ± 10,8 g. O rendimento médio de carcaça foi de 19,1 ± 2,8%, valor inferior ao relatado na literatura. As diferenças observadas foram atribuídas a fatores metodológicos e biológicos, como idade, genética e condições de criação. Conclui-se que os muçuãs apresentam perfil morfométrico compatível com a literatura e rendimento de carcaça relevante para sistemas produtivos sustentáveis na Amazônia.

Palavras-chave: Quelônios. Quantidade de Carne. Tamanho de Quelônio.

RESUMEN
El muçuã (Kinosternon scorpioides) posee importancia económica y social en la Amazonía, siendo ampliamente consumido por la población local. Este estudio tuvo como objetivo evaluar la morfometría y el rendimiento de canal de muçuãs criados en cautiverio en la Isla de Marajó, Pará, Brasil. Se utilizaron 26 (veintiséis) ejemplares de hembras adultas, de cuatro años de edad, provenientes de una cría autorizada. Los análisis morfométricos incluyeron mediciones del caparazón y del plastrón. Para la evaluación del rendimiento, se determinaron el peso vivo y los rendimientos de carne, vísceras y canal. Los muçuãs presentaron una longitud media del caparazón de 15,1 ± 0,7 cm y un peso medio de carne de 54,5 ± 10,8 g. El rendimiento medio de canal fue de 19,1 ± 2,8%, valor inferior al reportado en la literatura. Las diferencias observadas se atribuyeron a factores metodológicos y biológicos, como la edad, la genética y las condiciones de cría. Se concluye que los muçuãs presentan un perfil morfométrico compatible con la literatura y un rendimiento de canal relevante para sistemas productivos sostenibles en la Amazonía.

Palabras clave: Quelonios. Rendimiento de Carne. Tamaño del Quelonio.

1 INTRODUCTION

The muçuã (*Kinosternon scorpioides* Linnaeus, 1776) is a freshwater, semi-aquatic animal, commonly known as the mud turtle or musk turtle, and this is due to the habit of living in areas with high water density, and also to the strong odor they propagate when handled (MURPHY, 1997; CROTHER, 1999; BERRY and YVERSON, 2011). Its geographical distribution covers a vast area, being recorded and described in different countries in Central and South America (BERRY and YVERSON, 2011).

These animals live in flooded fields that dry up in the summer, which favors the illegal capture of the species, since it is appreciated in the local cuisine and makes up the dish called "casquinho de muçuã" (CASTRO, 2006). They are found with great ease in the region known as the Amazon Delta, where the island of Marajó/PA is located (BRITO *et al.*, 2016). The shell and eggs of the muçuãs have medicinal uses, and as the only representative of the Kinosternidae family in the Brazilian Amazon, they are a genetic resource to be preserved (MOLINA, 1989).

Brazilian legislation (BRASIL, 2017/2020) classifies muçuã as fish, however, the gap left by the absence of complementary rules specifically for the species is noticeable; This fact makes well-established operations for other species a complete challenge, both for production and to determine the carcass yield of the species.

Carcass yield refers to the proportion of carcass mass in relation to the live weight of the animal, and is an important indicator of production efficiency (CASTRO, 2006). The evaluation of carcass yield allows estimating the production potential of meat and other by-products of muçuã (FERREIRA *et al.*, 2017), as well as optimizing management and slaughter practices for sustainable and economical production.

This study aimed to evaluate the morphometry and carcass yield of muçuãs raised in captivity on the island of Marajó/PA, knowing the economic and social importance of the species for the Amazon Region.

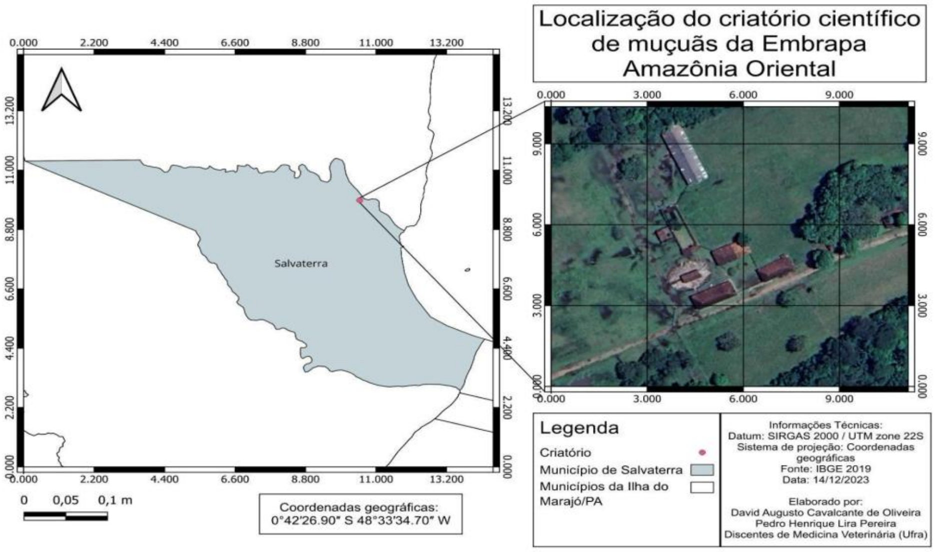
2 METHODOLOGY

The research was authorized by the Animal Ethics Committee of Embrapa Eastern Amazon, under protocol n0 001/2016, and the animals registered in process n.^{the} 0000032636, Operating License No.^{o} 7310. The analyses were carried out at the Laboratory of Analysis of Products of Animal Origin of the Institute of Animal Health and Production (Lapoa/Ispa), of the Federal Rural University of the Amazon (Ufra/*Campus* Belém-PA).

A total of 26 (twenty-six) adult females aged four years, from the captive breeding of Embrapa/Eastern Amazon, were used, referring to the project "In *situ conservation studies* of muçuã populations on the island of Marajó", Figure 1.

Figure 1

Visual representation and location of the captive breeding of muçuãs from the Animal Germplasm Bank of the Eastern Amazon/Bagam (geographic coordinates: 0°42'26.90"S and 48°33'34.70"W), Salvaterra-Marajó Island/PA. Map prepared in the Quantum Geographic Information System (Qgis)



Source: The authors (2024).

The animals were euthanized by administration of ketamine 20 mg/kg/IM, followed by a lethal dosage of propofol 30 mg/kg/IV, by adjustment of three times the non-lethal dosage of the protocol defined by Santos *et al.* (2011) for *Podocnemis expansa*. This method aimed to ensure unconsciousness before any physical and mental suffering, according to the guidelines contained in the Guidelines for the Practice of Euthanasia of the National Council for the Control of Animal Experimentation (Concea).

After death, fifteen animals were eviscerated (G2), while the remaining eleven were not eviscerated (G1) — this division as to the occurrence or not of evisceration was made due to the fact that the present study was carried out together with the analysis of the influence of evisceration on the centesimal composition of these same individuals in another study. Then, all animals were frozen in a domestic freezer at -18 ºC.

The PI (Weight of the whole animal) of G2 (n=15) is unknown because they were eviscerated before freezing in a previous study, without having recorded their initial weight prior to evisceration. Therefore, G2 was not used to obtain yield, but only for morphometry, since the calculation of yield depends on the PI.

For statistical analysis, Pearson's correlation analyses were performed and the construction of a graph of the importance of yield values as a function of morphometric variables were performed.

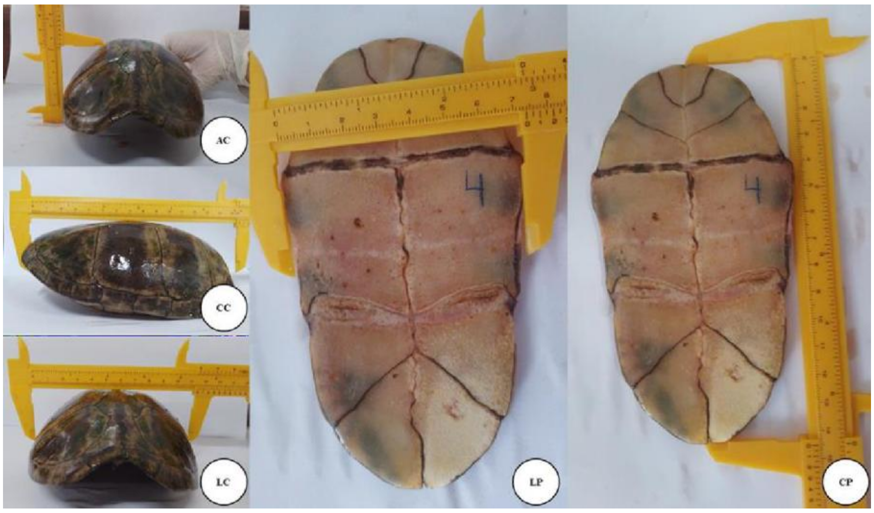
2.1 BIOMETRIC PARAMETERS

2.1.1 Morphometry

The morphometric proportions of plastron length (CP) and carapace (CC); plastron width (LP) and carapace width (LC); and dorsal carapace height (AC) of 26 specimens of *K. scorpioides were analyzed* (Figure 2).

Figure 2

Detailing of the morphometry methodology, highlighting the measurement of length, width and height of carapace and plastron. CC = Carapace length; LC = Carapace width; AC = Dorsal carapace height; CP = Plastron length; LP = Platron width



Source: The authors (2024).

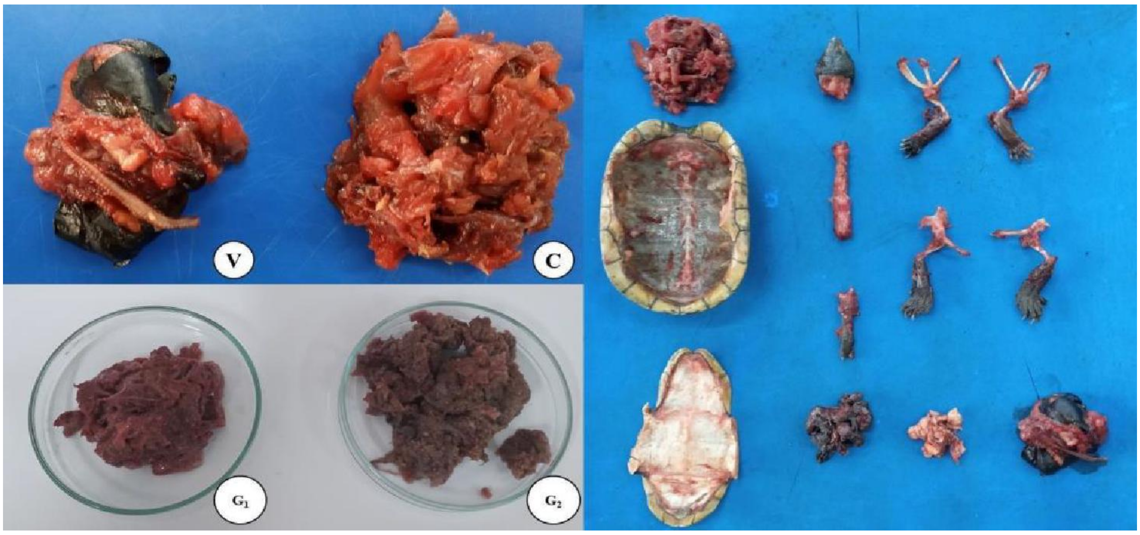
2.1.2 Income

The weight of the whole animal (PI) was obtained only for G1, because G2 had already been eviscerated before freezing, without recording its yield, and therefore its initial weight was unknown. It was still possible to obtain the meat weight (BW) of G2, although it was not possible to use this value to calculate the meat yield (CR), because this calculation depends on the knowledge of its IP.

Meat (CR) and viscera (RV) yields, obtained only for G1, were determined directly by weighing on an electronic scale, after removing the head, plastron, carapace, fat and bones (Figure 3), as well as a toilet to remove skin and dark muscle residues.

Figure 3

Visual representation of meat (C) and offal (V); comparison between meat obtained from G1 and G2, and visualization of hoof, meat, viscera, bones and fat obtained after complete desiccation of K. Scorpioides



Source: The authors (2024).

The carcass weight comprised the sum of the weights of meat, bones and fat, according to Article 277, Chapter VIII, of RIISPOA (BRASIL, 2017/2020). The following equations were used:

$$\text{Meat Yield (RC)} = \frac{\text{Meat Weight (BW)} \times 100\%}{\text{Whole weight (PI)}}$$

$$\text{Viscera Yield (RV)} = \frac{\text{Viscera Weight (PV)} \times 100\%}{\text{Whole weight (PI)}}$$

$$\text{Carcass Yield (RCÇ)} = \frac{\text{Carcass Weight (PCÇ)} \times 100\%}{\text{Whole weight (PI)}}$$

For the G2 group, there was no OR, LR or RCÇ because the calculations depended on the knowledge of their initial weight.

3 RESULTS AND DISCUSSION

3.1 MORPHOMETRY

The results of the morphometric determination of the muçuãs are presented in Table 1.

Table 1

Morphometry (cm) of the carapace and plastron. SD = standard deviation; Min = minimum; Max = maximum; CC = Carapace length; LC = Carapace width; AC = Carapace height; CP = Plastron length; LP = Plastron width

	General (n=26)			**G1** (n=11)			**G2** (n=15)		
Measure	**Average±DP**	**Min**	**Max**	**Average±DP**	**Min**	**Max**	**Average±DP**	**Min**	**Max**
CC	15.1±0.7	12,5	15,8	15.2±0.3	14,6	15,5	15.0±0.8	12,5	15,8
LC	10.4±0.5	9,6	11,7	10.1±0.2	9,6	10,3	10.7±0.6	9,8	11,7
AC	5.7±0.3	5,0	6,5	5.7±0.2	5,4	5,9	5.7±0.4	5,0	6,5
CP	14.0±0.5	13,0	15,3	13.8±0.5	13,0	14,5	14.1±0.5	13,2	15,3
LP	8.4±1.0	6,2	10,1	8.6±0.7	7,5	10,1	8.3±1.1	6,2	9,6

Source: The authors (2024).

The muçuãs had an average of 15.1cm (±0.7) carapace length, which is within the measurements already reported for the species, when considering the sex and age of 4 years (CASTRO, 2006). Neto (2018) observed, in a group of 165 individuals, a length of 14.81cm (±0.09), similar to Ferreira *et al*. (2017), which, analyzing 15 specimens, obtained a value of 14.7cm (±0.6). However, measurements lower than these were found by Ferreira (2023), who, studying 262 animals, obtained a measurement of 11.06 cm (±1.08). These differences, as well as that of the other morphometric measurements, can be attributed to the animal populations studied, rearing conditions, measurement methods or especially to age differences.

No major differences were observed between groups G1 and G2 in terms of morphometric results.

3.2 YIELD

The results of the carcass yield of the muçuãs are presented in Table 2.

Table 2

Weighing (g) of meat, offal and whole animal; and yield (%) of meat, offal and carcass for groups G1, G2 and General. SD = standard deviation; Min = minimum; Max = maximum; CP = Weight of the meat; PV = Viscera weight; PI = Weight of the whole animal; RC = Meat yield; RV = Viscera yield; RCÇ = Carcass yield

	General (n=26)			**G1** (n=11)			**G2** (n=15)		
Measure	**Average±DP**	**Min**	**Max**	**Average±DP**	**Min**	**Max**	**Average±DP**	**Min**	**Max**
PC	54.5±10.8	36,9	82,0	56.8±12.2	38,3	82,0	52.8±9.6	36,9	70,0
PV	–	–	–	50.1±10.1	39,5	69,8	–	–	–
IP	–	–	–	510.0±32.6	470,0	560,0	–	–	–
RC	–	–	–	11.1±2.2	7,6	15,0	–	–	–
VR	–	–	–	9.8±1.9	7,1	12,8	–	–	–
RCÇ	–	–	–	19.1±2.8	14,6	24,2	–	–	–

Source: The authors (2024).

In total (n=26), BW was 54.5g (±10.8) and for G1 (n=11) LW was 50.1g (±10.1). Similarly, Ferreira *et al*. (2017), using 15 specimens over 2 years of age, obtained similar results, with minimum and maximum BW of 43.8g to 85.0 g, respectively. These results demonstrate the efficiency in the use of resources and profitability for the muçuã producer, as they represent service to the local consumer market, ensuring adequate supply of meat (BRAZIL *et al.*, 2025).

Regarding yields, RCÇ and RV have greater commercial importance in the Amazon (BRAZIL *et al.*, 2025), as *K. scorpioides* is consumed as a "muçuã shell", a typical dish of regional cuisine in which meat and viscera are used. In this study, it was only possible to determine the PI for the animals in the G1 group (n=11), so OR, RV and RCÇ were only calculated for this group, although it was still possible to obtain the WC of G2. The OR obtained with deboning was 11.1% (±2.2), a result lower than the 15.0% (±1.7) obtained by Ferreira *et al.* (2017).

The animals in the present study showed 19.1% (±2.8) carcass yield, which differs from what has been reported for the species. Neto (2018) observed an RCÇ of 29.28%, while

Ferreira *et al.* (2017) obtained a value of 27.5% - obtained by the algebraic sum between 15.0% (±1.7) of the OR and 12.49% (±3.65) of the bone yield. Differences in results between experiments can be attributed to differences in methodology, including slaughter protocols, nutrition, genetics, and environmental conditions. Variations in the sample, such as age, race, and sex, also play a significant role in the results (YOUNG *et al.*, 2001).

3.3 MORPHOMETRY-YIELD CORRELATION

Table 3 shows the relationship between the morphometric parameters and the yields obtained for *K. scorpioides*.

Table 3

Pearson's correlogram for morphometric variables and yield. Plastron Length (CP), Plastron Width (LP), Carapace Width (LC), Carapace Length (CC), Carapace Width (LC), Carapace Height (AC), Whole Animal Weight (PI), Meat Yield (RC), Viscera Yield (RV) and Carcass Yield (RCÇ) of G1 (n=11)

	CP	LP	CC	LC	AC	IP	RC	VR	RCÇ
CP	1,00	- 0,4981 (0.119)	0,248 (0.462)	0,377 (0.252)	-0,838 (0.806)	0,624 (0.0399*)	0,919 (0.788)	-1,076 (0.753)	0.148 (0.664)
LP		1,00	0,194 (0.566)	0,288 (0.389)	-0,5790 (0.062)	-0,355 (0.284)	-4,251 (0.192)	-1,709 (0.615)	-0.187 (0.581)
CC			1,00	0,2310 (0.494)	-0,354 (0.285)	0,606 (0.048*)	-0,241 (0.944)	-1,742 (0.601)	0.0366 (0.915)
LC				1,00	-0,417 (0.202)	0,363 (0.272)	-2,671 (0.427)	0,588 (0.864)	-0.132 (0.699)
AC					1,00	-0,184 (0.587)	4,916 (0.125)	-1,485 . (0,663)	0.215 (0.525)
IP						1,00	1,596 (0.639)	-1,593 (0.640)	0.133 (0.697)
RC							1,00	1,797 (0.597)	0.899 (0,0001**)
VR								1,00	0.628 (0.165)
RCÇ									1,00

The P-value is recorded in parentheses below the corresponding Pearson's coefficient (R) and is interpreted as statistically significant evidence when ≤ 0.05 (*) and highly significant when ≤ 0.01 (**)
Source: The authors (2024).

Considering only the correlations with p-value<0.05, there was a positive correlation (R>0) between PI and NC (0.0399*), as well as PI and WC (0.048*), as already observed by

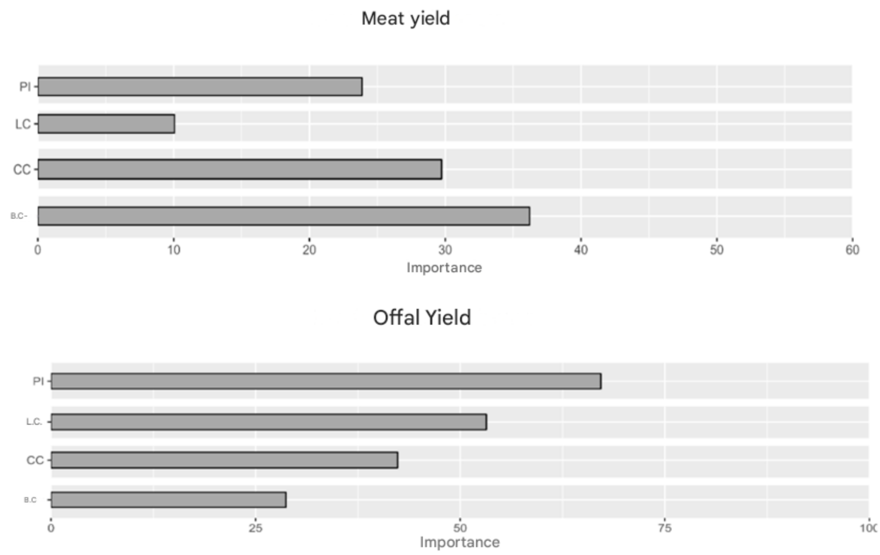
Castro (2006). The CR showed a positive correlation (p-value<0.01**) with the RCÇ, which was already expected due to the fact that the carcass weight is made up of the weight of meat, bones and fat (BRASIL, 2017, 2020).

No correlation was observed between morphometric measurements and yields (p-value>0.05). This fact can be attributed, in part, to the possible influence of the animal's age, according to Castro (2006), who observed that the p-value of Pearson's correlations between various morphometric parameters and weight varied according to the animal's age. Therefore, in the same way, the present study may not have identified a relationship between these variables due to the reproductive age in which these muçuã females were, so that animals of larger sizes and weights have these high values in attribution to the development of the reproductive system and egg production, but not to carcass and viscera yield, because factors such as biological maturity have an impact on the morphometric-yield correlation (Castro, 2006).

Figure 5 illustrates the comparison between the importance of morphometric variables for CR and LR. This type of graph represents the contribution of an independent variable (such as LC, WC, and PI) to a parameter defined as a dependent variable (CR and RV) (JAMES *et al.,* 2013).

Figure 5

Graph of importance (%) of morphometric variables in relation to CR and RV Meat yield. LC = Carapace width; CC = Carapace length; LC = Carapace width; AC = Carapace height (AC); PI = Weight of the whole animal



Source: The authors (2024).

For the CR, greater importance was observed for the variables CA, WC and PI, which means that these characteristics determine most of what the CR is (JAMES *et al.,* 2013). Biologically, these characteristics are related to the health and nutrition of the muçuã, as well as to the age group and sexual maturity, since healthy and sexually mature animals tend to have different physical characteristics that can influence meat yield (CASTRO, 2006). Similarly, for the RV, the PI, LC and CC are of greater importance, probably because they are associated with anatomical development and the proportion of internal organs in relation to the total size of the animal's body.

4 CONCLUSION

The muçuãs raised in captivity on the island of Marajó presented a morphometric profile according to the data found in the literature, considering age and sex, and which may be associated with considerable meat and viscera yield.

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