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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

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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

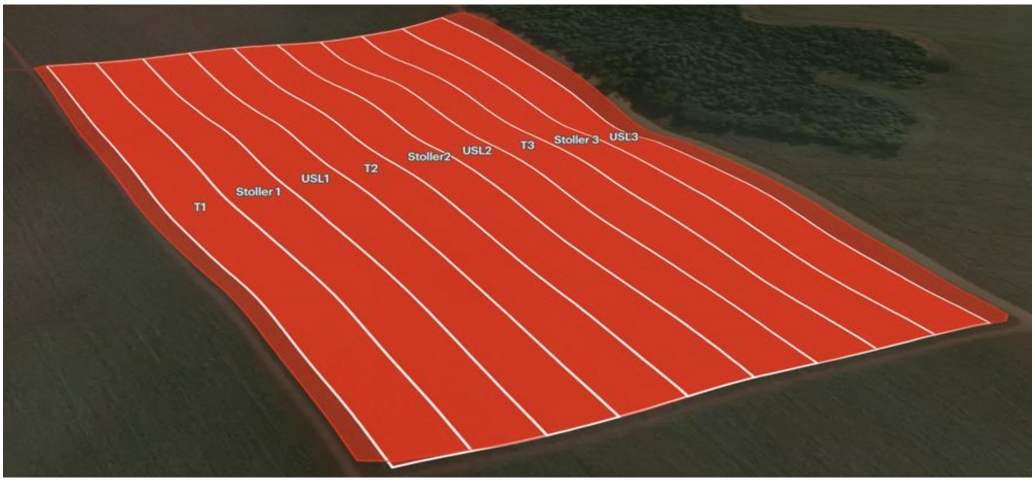


Figure 3

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.

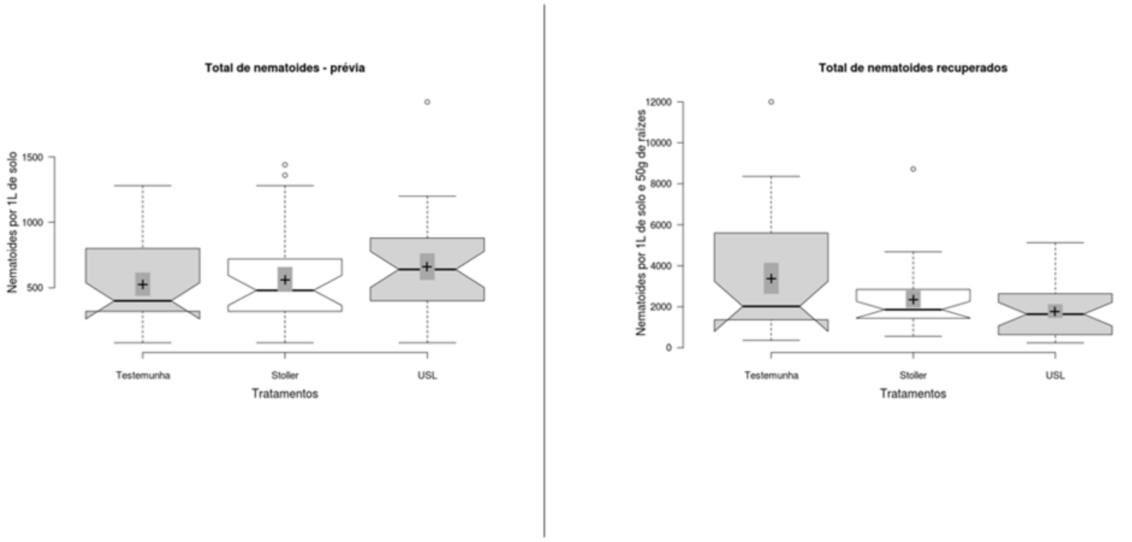
The results indicated a significant reduction in nematode populations in the treatments that received the products from Stoller and the Plant, with emphasis on the Enraíze + Root Top protocol. The total population of phytonematodes fell by 47.1% sixty days after application, and maintained 15.8% of residual 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.

[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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