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Proposal for TRL Adjustment in the Maturation of Agroindustrial Technologies

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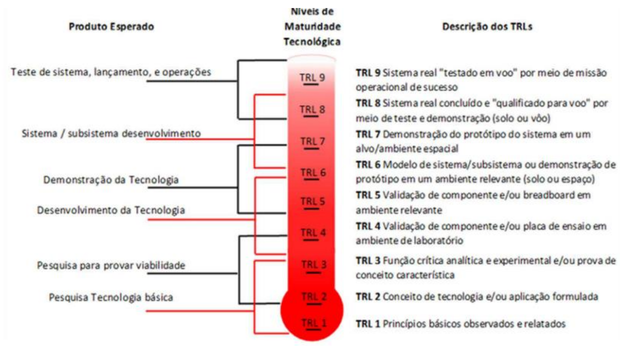
Abstract: Technology Readiness Levels (TRL) measure the maturity of technologies and are traditionally applicable to physical products and engineering systems. Although widely adopted by governments and industries, its use presents limitations when applied to areas such as agroindustry, which often rely on descriptive and methodological processes without tangible technological deliverables. In this context, it becomes necessary to adapt TRL to include methods that, although not resulting in a physical product, directly contribute to technological development. This study proposes an adaptation of the TRL scale for application in conceptual projects, especially in agroindustry, focusing on the maturation of protocols, planting methodologies, and technical processes. A systematic literature review, with searches carried out in the ScienceDirect and Scopus databases, revealed a lack of approaches that consider processes without a final product in the agricultural sector. As an example, the BRAVE-MEC project by Senai CIMATEC, aimed at producing bioethanol from *Agave sp.*, employs TRL to assess the maturity of planting methods. The adapted proposal redefines TRL levels to include stages such as ideation, scientific validation, proof of concept, and tests on different scales, culminating in commercial application. This new approach provides greater clarity, uniformity, and applicability in agroindustrial projects, ensuring effective communication among researchers and facilitating the evaluation of maturity levels for descriptive technological processes.
Keywords: Readiness Level; Agroindustry; Adaptation
Abbreviations: TRL

1. INTRODUCTION

Developed by NASA in the 1970s, the Technology Readiness Level (TRL) serves as a metric parameter for standardizing technological maturity, facilitating technology development by providing greater technical and operational credibility and reliability, as well as reducing investment risks [121-76]. It is divided into nine parameters, ranging from 1 to 9, and four phases: Concept, Prototype, Validation, and Production [3-87] (Figure 1). Lower TRL levels (low technological maturity) carry higher investment risks [12-7].

In 1974, Stan Sadin defined the initial scales containing seven levels of technological maturity, later refined in 1990 to establish two additional levels, totaling nine parameters. The model gained prominence in industry and government and has been widely adopted as the standard framework for technology assessment—supporting everything from scientific investigation for initial technology validation (TRL 1) to the final product stage and market application (TRL 9) [12-7]. TRLs are numbered from 1 to 9 (Figure 1) to measure the readiness of a given technology and track its improvement, maintaining clear, unified, and simple communication so all stakeholders can understand the project [1-7-9-12].

Figura 1 – Technology Readiness Level scales – TRLs



Source: Adapted from NASA (2007)

The TRL model assumes a linear process of technological development, from laboratory to market. Even with its wide applicability, it presents operational environment limitations, subjective evaluation definitions, and an origin and focus restricted to the aerospace sector, emphasizing well-defined physical products and mechanical systems [12-7]. This situation reveals challenges in applying TRL across various fields—such as healthcare, agroindustry, and chemistry—which have different perspectives that influence project development. Adaptations are therefore necessary, especially for theoretical research and development work [12-7].

In agroindustry, technological development may involve physical products (fertilizers, equipment) but also stems from the production and maturation of processes, such as protocols and methodologies that lead to satisfactory products. This requires adaptation to fit within the TRL framework [11]. Literature shows new TRL approaches in different sectors (health, energy, etc.), each with its own adaptations and definitions [12-7].

For example, EPAGRI (2022) adapted TRL to various technological categories in line with its rural and fisheries technology projects. Examples include: A cultivar developed and registered and its respective modifications in the TRL scale: TRL 3 – Pre-breeding stage (collection, exchange, multiplication, and characterization of germplasm in collections or Active Germplasm Banks – AGBs). Carrying out hybridizations or using auxiliary techniques to generate genetic variability, followed by selection based on descriptors; TRL 6 – Evaluation and selection of desired agronomic traits in the material obtained under commercial field conditions (spacing, phytosanitary treatments, others); TRL 9 – Licensed or granted cultivar in use within the production chain, with adoption monitoring [5].

In this context, the United States Department of Defense and Department of Energy have addressed new interpretations and adapted TRL into HRLs (Human Readiness Levels), aiming to understand the relationship between humans and technology, especially in complex systems that can critically affect humans, as well as the models System Readiness Level (SRL) and Manufacturing Readiness Level (MRL), used for the integration of systems and technologies and for product manufacturing, respectively [6-8-9-11] (Table 1).

The present work aims to present an adaptation proposal that encompasses application in exclusively conceptual projects, particularly in the agroindustrial sector.

2. METHODOLOGY

This literature review followed a systematic review approach to identify, select, and synthesize studies related to the Technology Readiness Level (TRL) in its direct application and respective adaptations to encompass other processes inherent to technology. The research was conducted in the ScienceDirect and Scopus databases over a nine-year period (2016 to 2024), using the following descriptors: “technology readiness level”; “technology readiness level” AND “agriculture”; “technology readiness level” AND “TRL”; “technology readiness level” AND “agroindustry,” in Portuguese, English, and Spanish. The terms were applied to the title, abstract, and keyword fields to maximize the retrieval of relevant studies on the subject. After data collection, selection criteria were applied to materials without restricted access, assessing the title and abstract, and subsequently classifying them into: 1) Description of TRL; 2) Adaptation of TRL; 3) Presentation of the practical use of the TRL scale.

3. RESULTS AND DISCUSSION

From the survey, more than one thousand articles were found, with the main areas of study being agriculture, aircraft technology, and engineering projects. However, in the environmental sector, and especially in agriculture, no studies were found related to descriptive processes (methodologies, processes) without a final technological product (tangible product). It is therefore necessary to adapt TRL to include ecological, social, and knowledge co-production aspects, as well as non-technological procedures [2-12]. Technological development in the agroindustrial field is recorded in the literature for technologies that capture and store CO_2, biomass production, and agricultural machinery, among others. However, it is also present in descriptive processes based on cultivation techniques, pesticide application, and plant pathogen identification methodologies [1-4-6-7]. Therefore, the application of TRL to descriptive methods is unsatisfactory, and an adaptation is needed to encompass these processes while still enabling clear, objective communication and identification of the maturity level [2-9-12].

The applicability of TRLs in projects with tangible technology (physical product) is satisfactory; however, this is not the case in projects with theoretical deliverables due to definitional limitations, such as the concept of "prototype" [9-12]. The process of adapting the TRL scale is common in the literature (Table 12), bringing changes and adjustments according to other aspects that guide technology and that go beyond the standard TRL framework, encompassing new perspectives regarding technology, market parameters, multiple technologies within a complex system, among others [9-12].

Table 1 – Technology assessment methodologies.

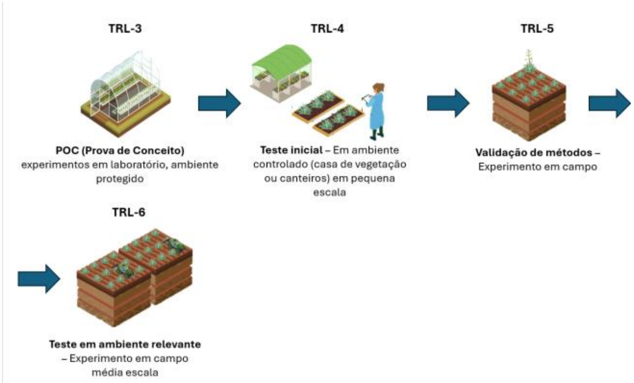
Model	Approach	Positive Aspects	Negative Aspects
Integration Readiness Levels (IRL)	Integration of components into a complex system	Evaluate component integration	Restricted to technical view
System Readiness Level – SRL	Risk assessment combining TRL with IRL	Combines component readiness with integration	Restricted to technical aspect, excludes obsolescence analysis
System Readiness Level Plus – SRL+	Integrates TRL, IRL, and MRL concepts	Broader technical assessment	Excludes obsolescence analysis
Technology life cycle	Evaluates technology maturity in its lifecycle	Anticipates trends and manufacturing risk	Avaliar o risco da manufatura no seu ciclo de vida. Buscar antecipar tendências.
Manufacturing Readiness Level (MRL)	Measures manufacturing maturity of a product, technology, or system	Manufacturing assessment	Assess the manufacturing risk in its life cycle. Seek to anticipate trends.

Source: Adapted from OLIVEIRA, André (2014)

From this perspective, an adaptation for applicability in the agroindustrial sector is already reported in the literature; however, it is limited to transgenics/gene editing, marker-assisted selection, bio-control, and tissue culture, all with a technological approach. A new perspective is therefore essential, as the development of diagnostic methods, planting methods, disposal methodologies, among others, is anticipated and would benefit from the use of TRL scales if properly adapted [9-11-12].

At Senai CIMATEC, with an emphasis on CIMATEC Sertão, projects are carried out based on TRL evolution, where descriptive methodologies (processes and protocols) that generate a final product are presented. In a case study analyzing the projects at CIMATEC Sertão, which bring solutions and innovations to the semi-arid region—such as the production of bioethanol from *Agave sp.*—planting methods are used, with TRL applied to define the stages and maturity, with the final goal of establishing a planting protocol for agricultural crops such as agave. In this study, TRL evolution is associated with the increased maturity of cultivation techniques, starting from scientific research (TRL 1/2) to nursery trials (TRL 3), plot trials (TRL 4), and finally field planting with TRL 5 and 6 (Figure 2), where the techniques used are validated, scale and environment are increased, and consequently, technological maturity is enhanced. Thus, it was necessary to adapt the scale for use in different areas.

Figure 2 – TRL evolution in *Agave sp.* planting



Source: Authors' elaboration

Terms like "prototype," "parts," and "pilot scale" were replaced with agricultural terms such as greenhouse, pots, plots, and experimental fields. Scaling was considered from laboratories to properties over 100 ha (1,000,000 m²), as relevant and operational agricultural environments can be large-scale.

The Brazilian Agricultural Research Corporation (EMBRAPA) and the Agricultural Research and Rural Extension Company of Santa Catarina (Epagri) have agricultural maturity recommendations covering products, methodologies, and agricultural production [5].

Accordingly, the proposed Technology Readiness Level adaptation (Table 2) replaces

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physical technology concepts with descriptive procedures that, when properly applied, result in a high-quality final technology.

Table 2 – TRL adaptation for the agroindustrial sector at Senai CIMATEC

Level	**TRL Adaptation**	Description
1	Ideation – bring the theme and start validating it	Technological and academic research
2	Scientific validation – search scientific databases to validate the idea	Technological and academic research
3	POC – Proof of concept; identify flaws or confirm potential before investment	Laboratory experiments, protected environments
4	Initial testing – in a controlled, small-scale environment	Protected environment, greenhouse, plot experiments
5	Method validation	Field experiments
6	Testing in relevant, medium-scale environment	Relevant field experiments
7	Large-scale test validation	Operational environment experiments
8	Validated procedures	Operational environment experiments
9	Commercial application	Operational environment experiments

Source: Authors' elaboration

This adaptation allows agroindustry projects to be carried out with a unified understanding, meeting research projections even when deliverables are limited to lower TRL levels—requiring consistent knowledge of the scale concepts throughout project maturation.

4. CONCLUSION

In conclusion, adapting TRL facilitates its use in maturing descriptive processes, such as methodologies and protocols that lead to a physical product, while maintaining a unified, clear, and objective language across the research network.

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