Critical analysis of application technology instructions in pesticide labels for Sorghum crops in Brazil

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Critical analysis of application technology instructions in pesticide labels for Sorghum crops in Brazil[1]

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ABSTRACT

Pesticide labels serve as the primary communication channel between manufacturers and users, providing essential information for effective and safe applications. This study critically assessed the application technology instructions provided on pesticide labels registered for sorghum crops in Brazil. Data were collected from the publicly available Pesticide Product Label System (AGROFIT) platform of the Brazilian Ministry of Agriculture, Livestock and Food Supply, from April 15 to September 13, 2021. The analysis encompassed various parameters, including formulation, application method, dosage and rate, spray solution preparation, weather conditions, growth stage/phase, application interval and number, adjuvants, spray nozzle type, droplet spectrum classification, size, density, coverage percentage, and working pressure. Our findings unequivocally demonstrate that the current application technology instructions on these labels are largely inadequate for promoting optimal application practices. This highlights the urgent need for more detailed and precise information, considering the complexity and variability of factors such as droplet size and distribution for spray penetration within the plant canopy, as evidenced in controlled studies. Such information is crucial for improving user communication, enhancing application efficiency and safety, and consequently, agricultural sustainability. This study emphasizes the urgent need for updated and comprehensive guidelines to bridge the existing information gap.

Keywords: Agrochemicals, regulation, application safety, information quality

INTRODUCTION

Pesticide labels serve as the primary communication channel between manufacturers and technical managers, offering essential information and guidelines for effective and safe applications. The quality of information on these labels is crucial for precise pest management recommendations and for guiding appropriate application techniques across diverse cropping systems.

Global and national pesticide consumption is substantial, with Brazil standing as a major consumer(1,2). However, this widespread use is frequently associated with improper application and indiscriminate use, leading to significant health and environmental concerns(3,4). Beyond volume, a critical aspect for both efficacy and safety is ensuring the active ingredient effectively reaches its biological target(3,5). This fundamental principle dictates that pesticide labels must provide clear and precise instructions on application precautions and procedures. Such guidelines are paramount for efficient droplet deposition, a complex process profoundly influenced by factors like nozzle type and droplet size distribution for effective spray penetration within the plant canopy(6). This efficiency minimizes risks of environmental contamination, worker exposure, and food contamination, and contributes to reducing the overall number and volume of pesticide applications(7).

Sorghum (Sorghum spp.) is an important global crop, particularly in Brazil, due to its adaptability to diverse growing conditions and its role in food and biofuel production(8). Given sorghum's increasing relevance and the critical role of proper pesticide application, a comprehensive assessment of the application technology instructions on pesticide labels specifically for this crop in Brazil is notably lacking in the literature. This gap is crucial, as inadequate instructions compromise both pest control effectiveness and application safety. We hypothesize that pesticide labels for sorghum crops in Brazil often provide insufficient application technology instructions, lacking the necessary detail for optimal and safe practices. Therefore, this study aimed to critically analyze these instructions, identifying their strengths and limitations, to highlight areas for improvement in communication between manufacturers and end-users.

MATERIAL AND METHODS

Information from pesticide labels registered for sorghum (Sorghum spp. [L.]) in Brazil was collected from the Pesticide Product Label System (Sistema de Agrotóxicos Fitossanitários – AGROFIT) platform, maintained and updated by the Brazilian Ministry of Agriculture, Livestock and Food Supply (Ministério da Agricultura, Pecuária e Abastecimento – MAPA).

The database search was performed using AGROFIT platform filters: "crop – sorghum" and "sort-by-brand." The "pest control product for organic farming" filter was also applied, leaving all other fields unselected. Executing the search displayed an alphabetically ordered list of products. Selecting a specific brand revealed product-specific data organized into tabs: "general information," "composition," "instructions for use/dosages," "documents," and "product label, label, and certificate," all containing relevant files.

From these open-source files, a database was compiled containing information from pesticide labels for 64 insecticides, 46 fungicides, and 50 herbicides. While pesticides are the primary class of pest control products sold globally[9], for this study, all pesticide labels available on the AGROFIT platform between April 15 and September 13, 2021, were analyzed. This specific timeframe was chosen to ensure data consistency by excluding subsequent registrations and potential label updates.

Comprehensive application technology checklists were prepared in Microsoft Excel spreadsheets, developed based on relevant literature and Brazilian regulatory guidelines, specifically Normative Instruction Nº 16/2017[10], to systematically extract information from the pesticide labels. These checklists meticulously covered a wide array of parameters, including: formulation; application methods (e.g., ground, aerial, seed treatment); dosage and application rates; detailed spray solution preparation guidelines (e.g., agitation requirements during preparation and spraying, water volume, water quality parameters including pH range, tank mix compatibility/incompatibility, spray solution shelf life, and product absorption period); weather conditions (pre-, during, and post-application recommendations); target-specific application strategies (e.g., mode of action, selectivity, developmental stage/phase, control level for application/reapplication, scheduled vs. threshold-based application, and target sampling methods); application frequency (interval and number of applications); adjuvant use (recommendation and specific identification); spray nozzle specifications (e.g., type, jet, droplet classification, size, and density); coverage percentage; working pressure; and critical safety and environmental precautions (e.g., pre-harvest interval, re-entry interval, buffer zones, personal protective equipment, and sprayer decontamination procedures). Additionally, physicochemical properties such as water solubility and vapor pressure, when available on the labels, were also recorded.

For each parameter, responses were classified following methodology[11] to demonstrate the presence or absence of information or recommendations. These were categorized as: “available,” “not available,” “not applicable,” “yes,” or “no,” depending on the product category. Numerical information was presented as: “exact value” (specific expression), “range” (values enabling technician selection), or “exact value and range” (multiple targets). “Not available” and “not applicable” classifications were also used.

From the results table, which included values and their frequency distributions, graphs were plotted using descriptive statistical tools following methodologies by[12,13]. These graphs represented the number of pesticide labels associated with each observation. All data were processed and organized in Microsoft Excel® for descriptive analysis, including percentage calculations and graph generation. The descriptive statistical tools and methodologies, including graphical representations, aligned with principles outlined by[14]. Categories were derived from nominal or ordinal categorical variables, consistent with the adopted classification approach. Frequency distribution tables were used for direct data comparison, and charts were created from table data when necessary.

RESULTS AND DISCUSSION

All pesticide labels for sorghum insecticides, fungicides, and herbicides specified their formulations. Suspension concentrates predominated for insecticides (48.4%) and fungicides (39.1%), while water-dispersible granules were most frequent for herbicides (50.0%) (Figures 1A, 1B, and 1C).

Formulation type influences product compatibility, mixture homogenization, and nozzle filter suitability. Homogenization in the tank, a significant challenge for application technology, applies to both single products and mixtures. In Brazil, the Pesticides and Related Products Registry (RAA) lists 68 registered formulations for pest control, with 17.6% for sorghum crops[15].

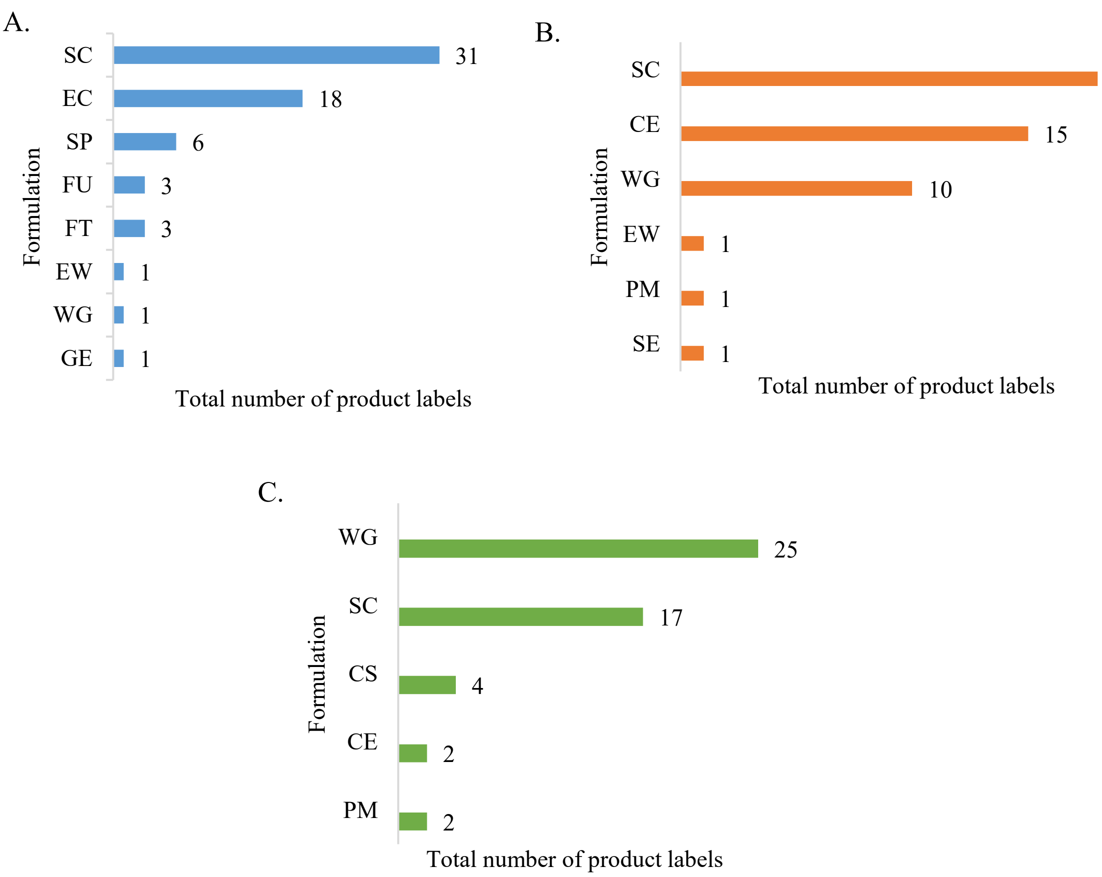

Figure 1. Types of formulations of insecticides (A), fungicides (B), and herbicides (C) used in products registered for the sorghum crop

SC, suspension concentrate; EC, emulsifiable concentrate; SP, water-soluble powder; FU, fumigant; EW, oil-in-water emulsion; FT, fumigant tablet; WG, water-dispersible granules; GE, gas generator; WP, wettable powder; EO, water-in-oil emulsion; SC, soluble concentrate.

Of 160 sorghum products, 41.3% were suspension concentrates for liquid applications (Fig. 1). The market presents diverse formulations—for dilution, direct application, seed treatment, and specialized forms (e.g., effervescent, baits, tablets, gas generators)[16]. The industry continually seeks alternative compositions to enhance spray solution balance and stability and reduce costs. However, analyzed labels lacked specific recommendations for formulations in concentrated spray solutions, a method gaining popularity in Brazil. This absence exposes a critical disconnect between efficient agricultural practices and outdated label guidance, potentially compromising application efficacy and safety.

All pesticide labels specified application methods. Insecticides showed 41.0% for soil or aerial, 30.0% for soil only, and 29.0% for seed treatment, stored grain protection, or traps. Fungicides indicated 63.0% for soil or aerial, 17.0% for soil only, and 19.0% for seed treatment. Herbicides reported 90.0% for soil or aerial and 10.0% for soil only (Figures 2A, 2B, and 2C).

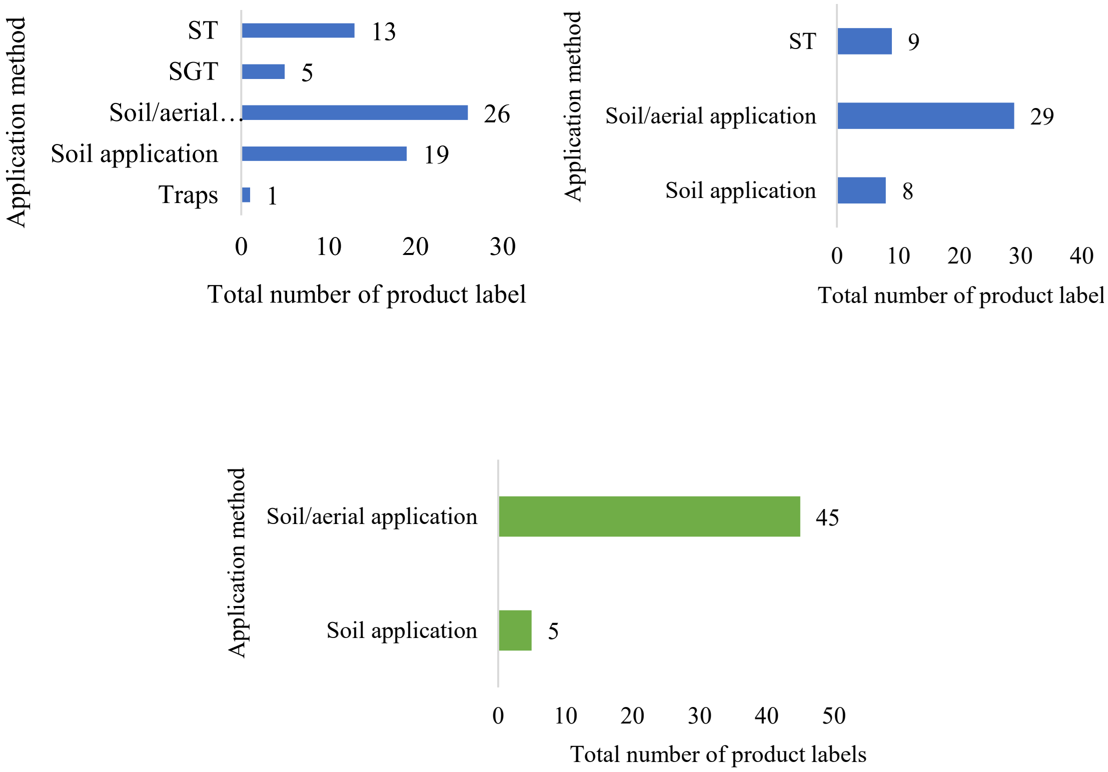

Figure 2. Application methods of insecticides (A), fungicides (B), and herbicides (C) recommended for the sorghum crop. ST: seed treatment; SGT: stored grain treatment

Analysis of 46 fungicide labels revealed a critical lack of specificity in application technology recommendations (Fig. 2). Notably, 63% grouped "Terrestrial/Aerial" recommendations generically. This constitutes a significant technical gap, as these modalities demand distinct operational parameters (e.g., spray volume, droplet spectrum, pressure) for effective target deposition and drift mitigation.

Different pesticide application methods offer new management opportunities, with studies[17,18,19] comparing soil and aerial approaches. Critically, no sorghum pesticide classes are approved for irrigation system application, despite its cost-effectiveness.

Aerial applications, conversely, involve legally mandated qualified staff and stringent regulatory supervision compared to soil applications.

Pesticide labels recommending aerial applications fail to differentiate between agricultural aircraft and remotely piloted aircraft (RPA). Despite Ministerial Directive nº. 298[20] establishing application "equivalence," this absence of specific label recommendations for either constitutes a significant regulatory and practical gap. Guidance is critical for tank mixture concentration and formulation stability, given their distinct operational characteristics. Agricultural aircraft and RPAs differ significantly in operational aspects, including spray pattern uniformity, droplet spectrum, and optimal flight parameters[21,22]. For instance, regulatory standards mandate decontamination areas for agricultural aircraft waste disposal, while RPAs discard waste over the crop. This highlights the need for distinct guidelines, as RPAs' smaller spray volume, lower flight altitudes, and precise targeting capabilities necessitate specialized instructions for maximizing efficacy and minimizing drift[17,18]. Thus, labels must provide specific recommendations reflecting these unique operational characteristics; lack of differentiation contributes to outdated information, hindering safe and effective adoption of advanced application technologies in Brazilian agriculture.

The analysis exposed a stark mismatch between label guidelines and emerging agricultural technologies: conspicuously, none of 46 fungicide labels for sorghum provided guidance on Unmanned Aerial Vehicle (UAV) application. This omission creates a dangerous regulatory and technical vacuum, leaving operators and agronomists without official recommendations on critical parameters (e.g., flight altitude, speed, UAV-specific spray volumes, drift mitigation). This underscores that pesticide labels fail to keep pace with technological innovation, leaving a common field practice without regulatory support and technical validation.

Effective communication hinges on commercial dosage presentations on pesticide labels. For insecticides, 56.0% of labels specified dosages as a range (allowing technician selection), 31.0% as an exact value, and 13.0% as both. Fungicide labels indicated an exact value in 60.0% of cases, a range in 38.0%, and both in 2.0%. Herbicides presented 50.0% as a range, 4.0% as an exact value, and 46.0% as both.

Effective pest control integrates population monitoring with integrated pest management, considering active ingredients and modes of action; dosage and timing are critical[(23)]. Fixed dosages on pesticide labels, irrespective of application method, complicate technicians' tasks. This rigidity, given spatial and temporal variability in severity, infestation, developmental stage, and species, renders fixed dosages potentially unsuitable. It fails to account for Brazil's vast agroclimatic and technical diversity in sorghum regions, hindering local adaptation. For example,[(24)] showed a fixed dose can induce herbicide hormesis in weeds if too low for a developmental stage.

Pesticide label application rates varied. Insecticide soil application rates were 45.3% range, 38.0% exact; aerial, 37.5% range, 1.56% exact. Fungicide soil rates were 52.2% range, 30.4% exact, 17.4% not applicable. Aerial fungicide applications were 50.0% range, 11.0% not provided, 39.0% not applicable. Herbicide soil rates were 84.0% range; aerial, 66.0% range, 14.0% exact.

Application rates are heterogeneously determined, typically by crop area or plant volume. In Brazil, area-based recommendations predominate, even for tree crops. Rates fluctuate with infestation severity, developmental stage, plant volume, and operational capacity. Recent efforts seek to reduce rates for increased efficiency[(21)], operational capacity, and cost reduction[19]. However, these updated rates are not consistently reflected on pesticide labels. For instance, sorghum pesticide labels omit RPA applicability, despite RPAs' significantly lower actual application rates compared to prescribed label rates. This disparity underscores a profound regulatory and communication gap, hindering efficacy and sustainability, and exposing applicators to unnecessary risks due to lacking specific modern equipment guidance.

Basic spray solution guidelines were often lacking. For insecticides, 70.0% of labels recommended agitation (96.0% during preparation, 47.0% during spraying). However, 19.6% of insecticide labels lacked guidance on agitation, solution shelf life, absorption period, or water chemical parameters for mixture preparation (Figure 3A).

Fungicide labels showed 87.0% provided preparation recommendations, and 85.0% agitation (78.8% during preparation, 78.0% during spraying). For water quality, 43.0% recommended high-quality water free of suspended colloids (e.g., soil, clay, organic matter), which can reduce product effectiveness (Figure 3B).

Herbicide labels indicated 86.0% for mixture agitation during preparation, and 34.0% for continuous agitation during spraying. Most labels did not specify water chemical characteristics for spray solution preparation; only 22.0% recommended high-quality water (Figure 3C).

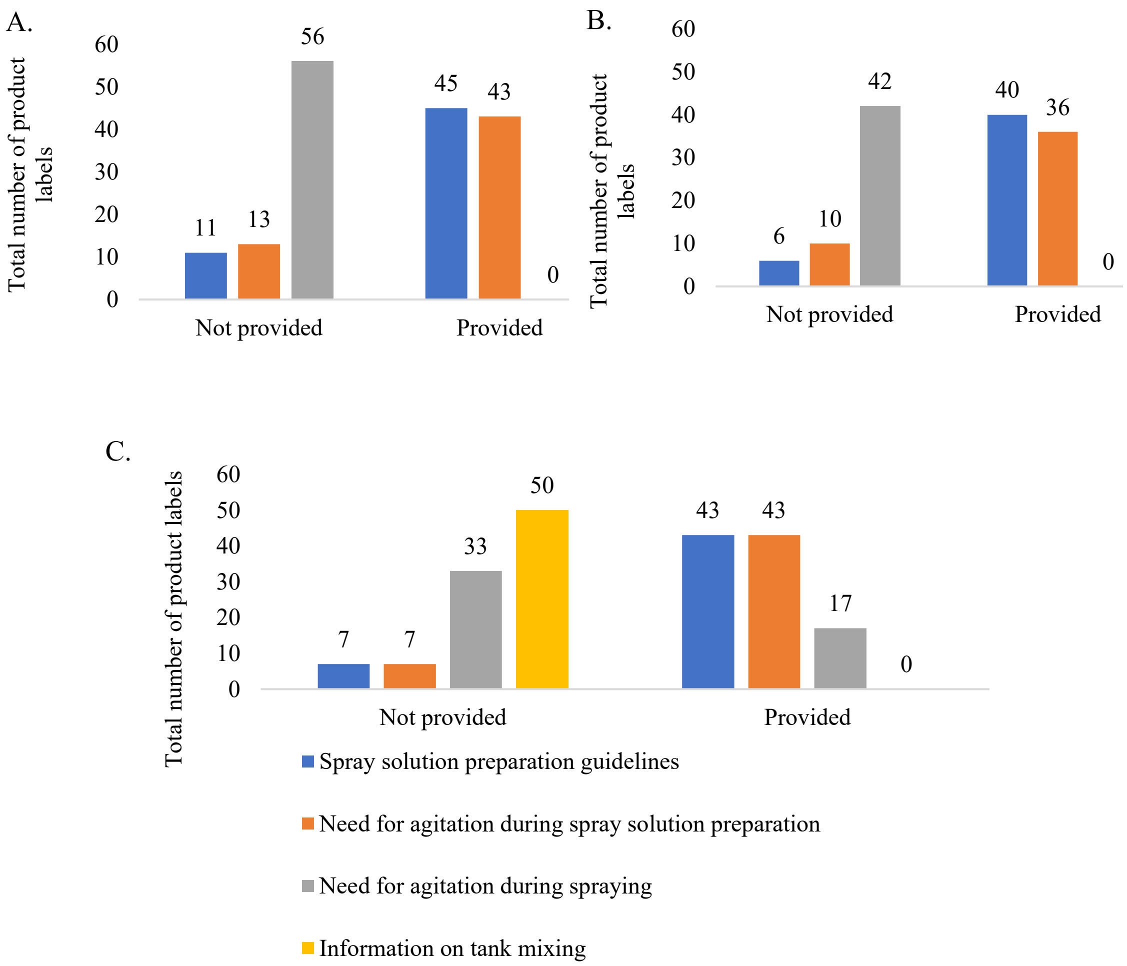

Figure 3. Guidelines on spray solution preparation provided in products classified as insecticides (A), fungicides (B), and herbicides (C)

Pesticide labels' indication of spray solution agitation is essential for technicians (Fig. 3). Hydraulic agitation systems, prone to inefficiency that reduces application effectiveness[25], demand attention. Mechanical systems, conversely, require well-maintained power transmission for homogeneous solutions[26].

Agitation quality affects spray solution homogeneity[26]. However, a significant deficiency emerged: no pesticide labels for fungicides, insecticides, or herbicides detailed instructions for sprayer tank mixing, a common field practice. Labels also consistently omitted information on product absorption period, solution shelf life, or performance post-rainfall. Crucially, many lacked essential water characteristics data, despite water pH's known impact on product physicochemical stability[27]. These omissions quantify risk, leaving technicians without fundamental guidance for safe, effective preparation, directly impacting application quality and environmental safety.

Weather conditions are essential for pesticide application, regardless of method[28]. However, only 64.0% of insecticide labels specified pre- and during-application weather conditions, with 9.0% for post-application. Fungicide labels showed 76.0% and 74.0% for pre- and during-application, respectively, and 13.0% for post-application. All herbicide labels covered pre- and during-application, but only 2% for post-application.

Brazil's diverse agricultural regions face widely varying weather, necessitating more informative pesticide labels on average temperature, relative humidity, and wind speed. Current generic instructions (e.g., RH > 55%, wind 3-10 km h^{-1}, temp < 30 °C) fail to provide nuanced guidance for sorghum's diverse microclimates and challenges. This regional specificity gap increases suboptimal applications, drift, and environmental contamination risks[29,30], underscoring the critical need for dynamic, regionally adapted meteorological guidance

Guidelines on the biological target's developmental stage, phase, or period are essential for technician recommendations. For insecticides, 20.0% of labels provided this information, and 50.0% specified application timing. Only 30.0% offered suitable control level information for recommendations, and 8.0% described a sampling method. However, 90.0% specified the number of applications for target pest control (Figure 4).

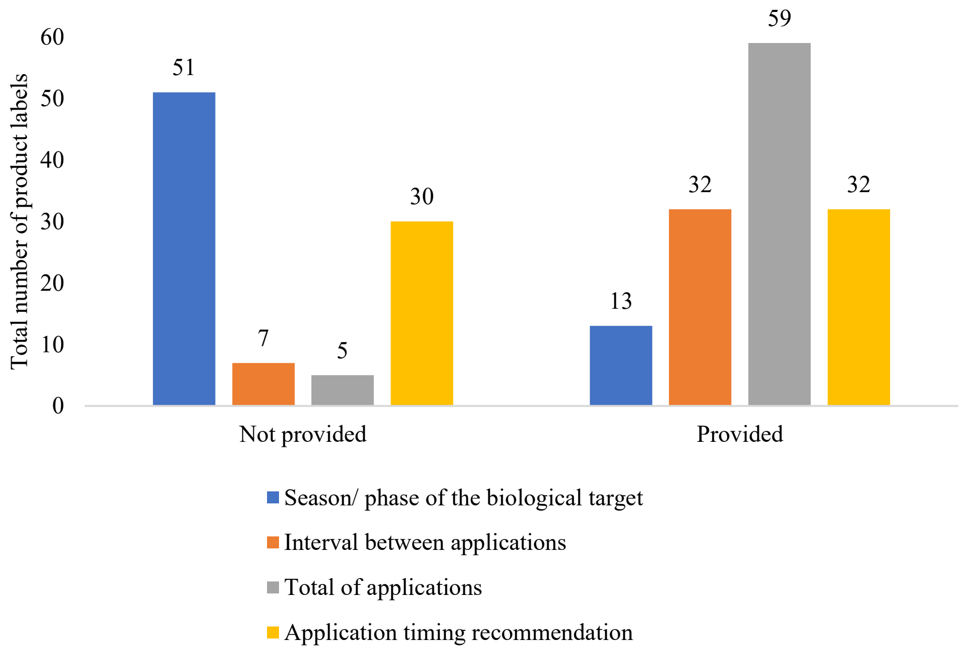

Figure 4. Characteristics of the biological target for insecticide application in the sorghum crops

Fungicide labels mentioned the target phase for application in 89.0% of cases (Fig. 4), but only 10.0% provided specific biological target details. The recommended number of applications was indicated on 98.0% of labels; interval between applications on 47.8%, and application timing on 48.0% (Figure 5).

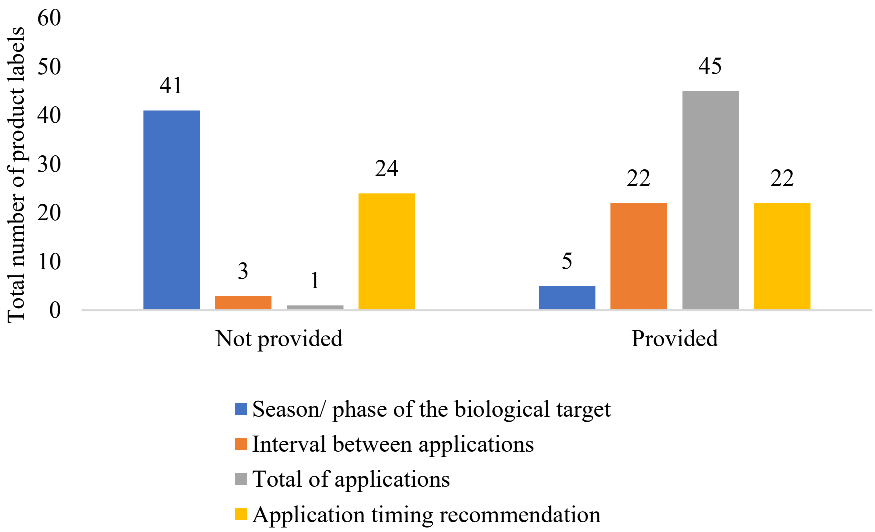

Figure 5. Characteristics of the biological target for fungicide application in the sorghum crop

Herbicide labels mentioned the target plant's developmental stage in 90.0% of cases, with 60.0% detailing specifics (Fig. 5). Recommended applications were specified in 88.0% of labels, while 18.0% described reapplication conditions. Sorghum herbicide selectivity appeared in only 32.0% of labels (Figure 6).

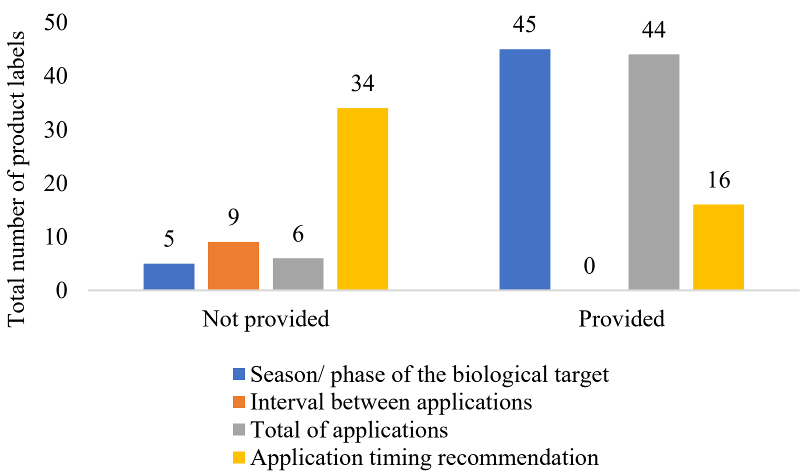

Figure 6. Characteristics of the biological target for herbicide application in the sorghum crop

Lacking descriptive/illustrative content on target phase, developmental stage, application number/interval, and selectivity hinders advances in pesticide application technologies and pest identification (Fig. 6). Despite the target development phase's critical importance for dosage/rate[31,32,33], our findings show few pesticide labels provide specific biological target details (e.g., 10.0% fungicides, 60.0% herbicides). This deficiency limits technicians' ability to implement precise, tailored pest management, contributing to suboptimal efficacy and potential overuse.

Adjuvants are commonly added to spray solutions[34]. However, only 3.0% of insecticide labels recommend this. Fungicides show 26.0% labels recommending, 15.0% identifying specific adjuvants. Herbicides have 78.0% labels recommending and identifying. Adjuvant dosage/concentration is typically a range for insecticides, exact for fungicides, and both for herbicides (48.0%). Different adjuvant classes exist, impacting application efficiency and droplet spectrum[35]. This lack of clear, consistent label instructions for adjuvant addition leaves technicians without essential guidance, potentially compromising efficacy, increasing off-target movement, and exposing regulatory oversight in application protocols. Clear adjuvant instructions significantly aid technicians in preparing solutions[22].

Specific spray nozzles and jets were recommended for insecticide (36.0%/37.0%), fungicide (41.0%/37.0%), and herbicide (78.0%/74.0%) labels, respectively. Spray nozzles determine droplet size, flow, application rate, and distribution, contributing to drift reduction[36]. Nozzle type and application rate also influence spray solution deposition, retention potential, and runoff[37].

Beyond nozzle recommendations, 9.0% and 11.0% of insecticide and fungicide labels indicated droplet class, and 42.0% and 41.0% indicated droplet size. Droplet size definition should be based on application rate, weather, biological target[38], and pesticide type[39]. For herbicides, 74.0% of labels indicated both droplet class and size

Droplet densities appeared in 29.0% of insecticide, 24.0% of fungicide, and 42.0% of herbicide labels. Among herbicides, 26.0% recommended an exact droplet population for effective control, a value challenging to achieve in the field due to varying nozzle conditions and sorghum regions[40]. Target coverage percentage was exact in only 1.6% (insecticides) and 2.0% (herbicides).

Merely reporting exact droplet density and target coverage values on pesticide labels does not foster good practices or advance technological knowledge. Spray nozzle, droplet class, density, and coverage should be primarily selected based on dynamic factors (e.g., weather, pest characteristics, application rates)[41,29]. These demand real-time adjustment for highly variable field conditions, a flexibility inherently limited by overly prescriptive label instructions (e.g., single droplet size/nozzle type). Such rigidity leads to suboptimal results or increased off-target movement[34]. Thus, rigid label recommendations for droplet size/spray nozzles, particularly for Brazil's diverse regions, impede technician education in modern application technologies and hinder precision agriculture adoption and advancement toward safer, more efficient practices.

Overall, pesticide labels provide insufficient or misleading information on appropriate application technologies. In conjunction with MAPA, companies must improve label updating processes to enhance application effectiveness and food safety.

CONCLUSION

This study confirms our hypothesis: pesticide labels for sorghum crops in Brazil frequently provide insufficient, misleading, or outdated application technology information, directly compromising application efficacy and safety. Our quantitative analysis demonstrated widespread deficiencies across critical parameters, including formulation, application methods, dosage, spray solution preparation, and environmental conditions. This problem is exacerbated by the rapid evolution of technologies like remotely piloted aircraft (RPAs), for which current labels offer virtually no specific recommendations. Despite existing legislation providing label guidelines, many offer minimal technical guidance for precise, regionally adapted pesticide applications. This critical gap leaves field technicians confused and increases risks. Therefore, an urgent, concerted effort is essential from public regulatory bodies and private sector manufacturers to modernize label updating processes. Pesticide label information must be rapidly updated to improve communication, include assertive and regionally adaptable recommendations, and explicitly address emerging technologies. Labels must evolve beyond mere compliance documents, becoming dynamic educational tools that foster best application practices. Ultimately, effective communication between manufacturers and end-users is imperative to enhance application effectiveness, ensure food safety, and promote the sustainable use of pesticides in Brazilian agriculture.

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DATA AVAILABILITY STATEMENT

All data supporting the results of this study are contained within this article.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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