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ARTICLE

Dose effectiveness and quality of soybean seed treatment in Brazilian agriculture as a function of application technology

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ABSTRACT: Seed treatment can be carried out in two modalities: On-Farm or via industrial treatment (IST). Evaluating the quality of the treatment is crucial, considering the percentage of coating by the phytosanitary product and the adequacy of the dose. In this context, the aim of this study was to evaluate the use of high-resolution computerized image analysis to assess the coating of treated soybean seeds. In addition, it was sought to characterize the quality profiles of coating and dose adequacy in treated seeds in the Brazilian agribusiness. 150 samples of seed treated in both modalities were collected from various soybean producers in Brazil and evaluated for the percentage of coating by means of color quantification in high-resolution image analysis and for the percentage of the active insecticide ingredient by means of High Performance Liquid Chromatography (HPLC). Image analysis was effective in quantifying coating, regardless of the dominant color. Coating correlated directly with dose effectiveness in the IST modality. Seeds treated via IST tended to have higher quality and homogeneity of treatment compared to On-Farm treated seeds, showing adequate coating and dose effectiveness. On-Farm treated seeds showed heterogeneity in treatment quality, with significant variation in coating and dose effectiveness.

Index Terms: chemical treatment of seeds, digital image processing, functional quality, seed coating.

RESUMO: O tratamento de sementes pode ser realizado em duas modalidades: On-Farm ou via tratamento industrial (TSI). A avaliação da qualidade do tratamento é crucial, considerando a porcentagem de recobrimento pelo produto fitossanitário e a adequação da dose. Nesse contexto, o objetivo neste trabalho foi avaliar a utilização da análise computadorizada de imagem de alta resolução na avaliação do recobrimento de sementes de soja tratadas. Além disso, buscou-se caracterizar os perfis de qualidade de recobrimento e adequação de dose em sementes tratadas no agronegócio brasileiro. Foram coletadas 150 amostras de sementes tratadas de ambas as modalidades em diversos produtores de soja do Brasil e avaliadas quanto à porcentagem de recobrimento por meio da quantificação de cor em análise de imagens com alta resolução e quanto à porcentagem do ingrediente ativo inseticida por meio de Cromatografia Líquida de Alta Eficiência (HPLC). A análise de imagem mostrou eficiência na quantificação do recobrimento, independentemente da cor dominante. O recobrimento possui uma relação direta com a assertividade da dose na modalidade de TSI. Sementes tratadas via TSI tendem a ter maior qualidade e homogeneidade de tratamento em comparação com as On-Farm, apresentando recobrimentos e assertividade de doses adequados. Nas sementes tratadas On-Farm, observou-se heterogeneidade na qualidade do tratamento, com variação significativa no recobrimento e assertividade da dose.

Termos para indexação: tratamento químico de sementes, análise computadorizada de imagem, qualidade funcional, recobrimento de sementes.

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INTRODUCTION

The growing perception of the value of seeds in Brazil has led the soybean seed industry to improve physiological, sanitary, and physical quality using processes, such as seed treatment, that promote quality or preserve performance in the field (Carvalho et al., 2021). Chemical treatment of seeds advances annually and represents about 1.5% of the production cost of soybean seeds (ABRASEM, 2020). Ensuring not only quality but also proper application and effective distribution is essential to fulfill its function given the variety of products applied (Reis et al., 2023).

Seed treatment can be carried out in two different modalities: On-Farm is carried out on the farmer's property usually with less precise equipment, and industrial treatment (IST) is carried out by farmers or specialized companies using specific equipment during seed processing and storage (Reis et al., 2023). IST allows the application of a variety of products, such as pestcides, micronutrients, and polymers (Bem-Júnior et al., 2020).

Seed companies still face a number of obstacles when it comes to making quick and accurate decisions about their internal quality control programs regarding seed treatment quality (Andrade et al., 2024). When compared with computer vision systems, the visual evaluation of seed treatment quality is considered subjective, often inaccurate due to standardization difficulties, and also monotonous and time-consuming. As a result, safer decision-making has been facilitated by new AI-based tools (Medeiros et al., 2023).

In recent years, research has focused its efforts on the exploration of computational methods aimed at assessing seed vigor and seedling development (Carvalho et al., 2020; Oliveira et al. 2021; Lima et al., 2023). In addition, these studies are also being conducted to assess the quality of seed treatment by quantifying the percentage of pesticide coating on the seed (Medeiros et al., 2023; Andrade et al., 2024), but there is still a lack of studies and adaptations. Medeiros et al. (2023) and Andrade et al. (2024) demonstrated that the coating of treated corn and soybean seeds, respectively, can be successfully measured using high-resolution image analysis. Thus, computer vision techniques are a promising alternative to evaluate the quality of seed coating. This is due to the urgency in decision-making in the seed industry, as well as the development of innovative methods, technologies, and appropriate instruments. However, these studies are the only ones that examine the coating and quality of seed treatment using this tool.

In this context, the aim of this study was to evaluate methodologies and parameters for validating the use of high-resolution computerized image analysis in the evaluation of coating of treated soybean seeds, as well as characterizing the profiles of coating quality and dose effectiveness in seeds treated with On-Farm technology and via IST in Brazilian agribusiness.

MATERIAL AND METHODS

Soybean seeds from different lots and cultivars were collected in producing regions of the Brazilian agribusiness in the states of *Minas Gerais, São Paulo, Goiás, Bahia and Mato Grosso*. Samplings were carried out in seed companies, resellers and grain-producing farms.

Samples were randomly collected in states of Brazil and were classified as IST seed samples or On-Farm seed samples. According to the logistical and economic feasibility of each region studied, 75 samples with IST modality and 75 samples with On-Farm modality were collected. The samples included only seed lots in which the use of the following insecticides by farmers was declared: thiamethoxam, chlorantraniliprole, cyantraniliprole, fipronil and imidacloprid. At least two kilograms of seeds were homogenized, identified and sent to represent each sample.

The samples were subjected to evaluation of seed treatment quality by means of the test of effectiveness of the dose of the active ingredient informed with High Performance Liquid Chromatography (HPLC), carried out at the *Seedcare Institute* – Syngenta, Holambra, SP, Brazil, and evaluation of the percentage of seed coating by phytosanitary products and functional products using capture and analysis of high-resolution images, carried out at the *Universidade Federal de Lavras* (UFLA), *Escola de Ciências Agrárias de Lavras* (ESAL), *Departamento de Agricultura* (DAG), *Laboratório Central de Pesquisa em Sementes* (LCPS), Lavras, MG, Brazil.

Effectiveness of the dose of the active ingredient: chromatography was only performed in On-Farm samples treated with thiamethoxam, chlorantraniliprole, cyantraniliprole, fipronil and imidacloprid, and in IST samples treated with thiamethoxam and cyantraniliprole. The samples were analyzed using the Agilent 1260 Infinity II instrument, which has a solvent compartment system, quaternary pump, injector, chromatographic columns, variable wavelength detector (VWD) and computer with analytical software (Agilent, 2022).

Analysis was carried out using 200 soybean seeds in triplicate for each of the samples. Specific solvents were added to the samples for extraction. An aliquot of the filtrate was collected and transferred to a volumetric flask. The content was then transferred to perform injections in the chromatograph and the reading of the data in the OpenLab software. Quantification of insecticides by HPLC was performed with the specific parameters used by the Laboratory of the *Seedcare Institute Latin America - Syngenta*, namely: chromatographic column, mobile phase, mobile phase flow, wavelength, injection volume and column temperature, with retention time of approximately 3.7 minutes. The software automatically calculated the result in grams of insecticide active ingredient per kilogram of seeds (Reis et al., 2023). In the analysis of the HPLC results, for dose effectiveness, the results obtained per sample were relativized as a function of the ideal dose, considered 100% (Medeiros et al., 2023).

Capture and analysis of high-resolution images for percentage of coating: the analyses were performed using the GroundEye® platform, version S800. For this evaluation, 2 tests were necessary, one to define and evaluate methodologies and parameters in the collection and processing of the images and the other to quantify the percentages of coating in the sample.

Test 1: Definition of parameters in the collection and processing of test images of the backgrounds.

IST samples contained red and pink colored products, while On-Farm samples were grouped into products with a variety of colors, including red, pink, blue, purple, and green. In view of the discrepancies in the colors of seed coating, it was necessary to study the initial configuration of the GroundEye® system, version S800, in relation to the background color to capture images with the proper contrast between the material of interest and the image background. A computerized image analysis test was performed to identify the background color with the best contrast in relation to the seed coating colors, thus establishing an analysis methodology to evaluate the seed treatments.

Images of soybean seeds treated in blue, green, red/pink and purple were captured and processed, with two replications of 50 seeds for each treatment and tested background color (yellow, black, blue, red and white). Then, a specific initial analysis was configured for each background, in order to obtain the best contrasts. The choice of the ideal background was based on the visual evaluation of the image detection efficiency, prioritizing greater contrast between treated seeds and background.

Test 2: Evaluation of percentage of coating of treated seeds

The coating percentage of treated soybean seeds was evaluated by capturing and processing images using the GroundEye® image analysis system, version S800. This system includes a capture module with an acrylic tray, a high-resolution camera, and integrated software for evaluation. The coating percentage of seeds with treatment was evaluated by image analysis. Soybean seeds were inserted into the tray of the capture module to obtain high-resolution images with the aid of a sowing tray, with analysis of 50 seeds for each replication of the treatments. The analysis for calibrating the background color was configured using the CIE L*a*b color model, with L index from 0.0 to 100.0, a index from -18.8 to 41.2 and b index from -56.1 to -6.5. The minimum size to discard the object was 0.08 cm^2, and interior filling was selected. This model was developed after several pre-tests. After calibrating the background, the images were analyzed using the Color: Dominance tool. The coating percentage of treated seeds was considered as the sum of the percentages of the dominant colors, defined by the color of the products used in the treatment. The results were expressed as a percentage relative to the analyzed surface.

Statistical analysis: the statistical design was completely randomized (CRD), with three replications. The data were subjected to analysis of variance at 5% significance level, using the F test, and when significant, the means were grouped using the Scott-Knott test with 5% significance level. The mean grouping tests were conducted using Sisvar® software (Ferreira, 2019). The data were also analyzed using descriptive statistics, with calculation of mean and coefficient of variation.

RESULTS AND DISCUSSION

After performing the background tests (*Test 1*) for defining parameters in the collection and processing of the images, the CIELab color parameter with lightness index of 0 to 100, dimension "a" of -41.2 to 18.8 and dimension "b" of 44.3 to 120.0 was defined for the analysis of images with yellow background. The CIELab color parameter with lightness index from 0 to 100, dimension "a" from -19.1 to 40.9 and dimension "b" from -42.6 to -20.0 was defined for the blue background. On the other hand, the red background was analyzed using the color parameter YCbCr, with luma index from 0 to 1.0, blue index from -0.15 to 0.01 and red index from 0.10 to 0.41. Regarding the parameters, the interior filling, minimum seed size of 0.08 cm^2 and dilation of -0.02 cm were used for all the background colors analyzed.

The initial color configuration proved to be ineffective to evaluate the treated seeds in the backgrounds with black and white colors. The blue background was chosen due to the most favorable results among the options evaluated. After capturing the images, the methodology and parameters presented in *Test 1* were applied to the analysis configuration for the blue background.

The yellow and orange color dominances were evaluated on the surface of the uncoated seeds, both On-Farm and IST. On the other hand, for the coated surface of these seeds, color dominance was analyzed as shown in Figure 1, excluding the colors that do not fit into this classification.

Regarding the results of the image analysis for seed coating percentage, a minimum of 73.54% and a maximum of 100% were observed in IST samples, representing a percentage difference of 26.46% between the extremes (Figure 2). For the On-Farm samples, the minimum mean was 1.52%, while the maximum mean was 99.99%, indicating a percentage difference of 98.47% between the extremes (Figure 2).

In the group of samples with the best coating percentages (73 samples, ranging from 100% to 95.2%), there was a significant predominance of IST samples (78%) compared to On-Farm samples (22%). On the other hand, in the group with the lowest coating percentages, of the seven samples considered the worst, there were no seeds from IST.

Considering the criterion suggested by Medeiros et al. (2023) of 90% for a satisfactory coating in treated corn seeds, in samples above this value, there were 75.5% of IST samples and 24.5% of On-Farm samples (Figure 2). For an excellent coating (values above 95%), the values found were 78% of IST soybean samples and 22% of On-Farm samples, reinforcing the trend of greater excellence in IST, although some On-Farm samples also reached this standard.

Figure 1. Classification of the dominant colors according to the color of the different seed treatments.

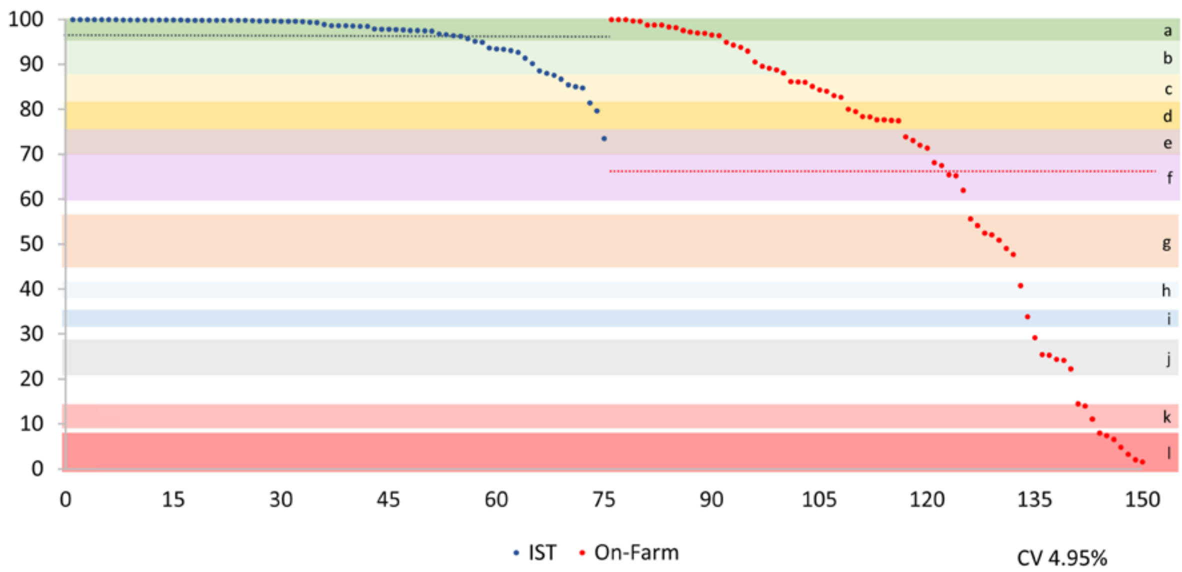

Figure 2. Separation of the samples into distinct groups as a function of the percentage of seed surface coating. Means followed by the same letter do not differ from each other by Scott-Knott test at 5% significance level.

Therefore, in this study, considering the sample profiles, minimum values of 90% for satisfactory coating and 95% for excellent coating are suggested in soybean seeds.

The greater coating in the IST modality is due to the advantages of the treaters used, as reported by Reis et al. (2023). Batch treatment or industrial continuous flow treaters in IST ensures better coating on soybean seeds, greater efficiency in dose application, less particle detachment and reduction in the occurrence of mechanical damage, compared to the On-Farm application technology. In addition, Soares et al. (2019) studied different treatment modalities in soybean seeds and observed that IST produced a better coating on the seeds, resulting in a higher seedling emergence rate in the field and higher grain yield.

These results highlight the importance of a phytosanitary treatment carried out correctly, not only to ensure the efficiency of the product in controlling pathogens and pests in the field, but also to avoid phytotoxicity. Several studies associate phytotoxicity with the spray volume used in seed treatment, as observed by Abati et al. (2020) and Pereira et al. (2021), who identified a reduction in soybean seed quality due to storage associated with the use of high spray volumes.

Another important parameter in the evaluation of the quality of the treatment is the effectiveness of the dose of the active ingredient, that is, the amount applied in relation to the desired amount. The mean effectiveness for IST samples ranged from 81.25% to 113.91%, indicating a maximum underdosage of 18.75% and a maximum overdosage of 13.91% (Figure 3).

On the other hand, for On-Farm samples, the variation was from 0% to 169.27%, with results of 0% indicating absence of the active ingredient identified by the farmer as used. Above the samples without the active ingredient, the minimum mean found was 27.06% of effectiveness, representing an underdosage of approximately 73%. The highest mean indicated an overdose of about 69%, highlighting the heterogeneity in On-Farm samples both in terms of coating and dose effectiveness (Figure 3).

Both underdosing and overdosing are detrimental to seed treatment quality. Underdosing compromises the efficacy of the product in relation to target pathogens and pests, while overdosing can compromise the physiological quality of seeds, often due to phytotoxicity, depending on the active ingredient used (Carvalho et al., 2021; Medeiros et al., 2023).

Considering a satisfactory range of dose effectiveness between 80% and 120%, it was found that, among the samples within this range, 70.75% came from the IST modality, while 29.25% were from On-Farm (Figure 3). These

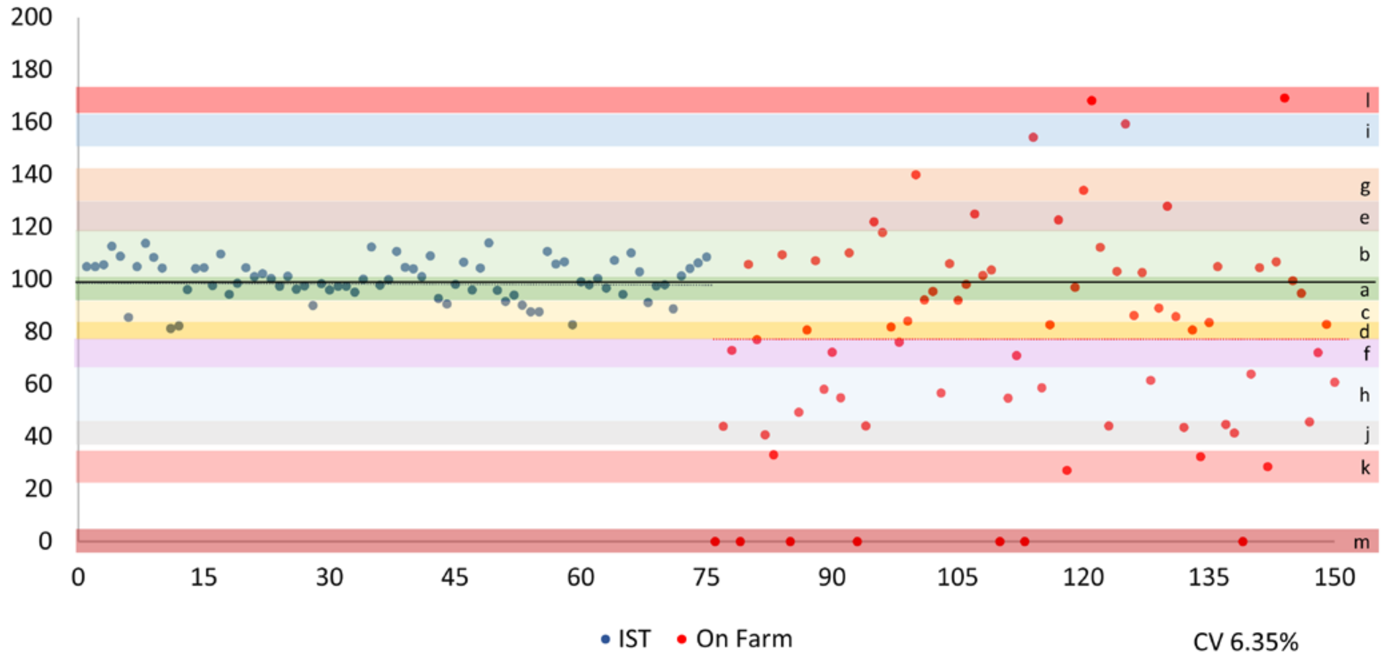

Figure 3. Separation of the samples into distinct groups according to the percentage of effectiveness of the dose of the active ingredient in the seeds. Means followed by the same letter do not differ from each other by Scott-Knott test at 5% significance level.

results reinforce the trend of greater dose effectiveness in soybean seeds treated via IST application modality, with some exceptions for On-Farm.

IST ensures superior efficiency in the application and distribution of products, ensuring uniformity in seed coating and accurate dosing (França-Neto et al., 2015). Reis et al. (2023) reported an efficiency above 99% in the coating of soybean seeds treated with IST, while in seeds treated with On-Farm, this value was 88%, thus corroborating the results obtained in the present study.

Figure 4 shows images of On-Farm and IST samples. As previously discussed, On-Farm samples showed a high heterogeneity in coating for all the different colors collected, duly quantified by means of high-resolution images. On the other hand, IST samples showed greater coating and homogeneity. Thus, there is a lack of uniformity in the color of the On-Farm treatment, even within the same predominant color of seed treatment.

With samples from several Brazilian states and based on the analysis of the results of the quality parameters discussed above, it was possible to identify different treatment quality profiles as a function of the technologies and application processes employed on the farm itself.

For the samples of the On-Farm treatment, different profiles of farmers were observed. Among them are those whose seeds had low coating and low dose effectiveness. For example, the V-V 109 sample, treated with a red pesticide, showed 1.52% of coating and 32.4% of effectiveness of the active ingredient, as also observed in the samples R-R 64 and R 237. These results indicate profiles of farmers with low application technology and technical assistance, a combination that is detrimental to treatment quality (Figure 5).

Low coating, but with overdose, was observed in some samples. For example, the V-V 240 sample showed 55.61% coating and 169.27% effectiveness; V-R 255 had 54.12% coating and 168.26% effectiveness; and V-R 1 exhibited 68.13% coating and 140% effectiveness (Figure 6). In this case, it is suggested that the farmer, in an attempt to obtain a good coating, increased the recommended dose of the product. However, even with an addition of up to 70% of the active ingredient, it was not possible to obtain a satisfactory coating, probably due to the lack of an efficient application technology, combined with a predominantly aqueous solution, making it difficult to identify the coating.

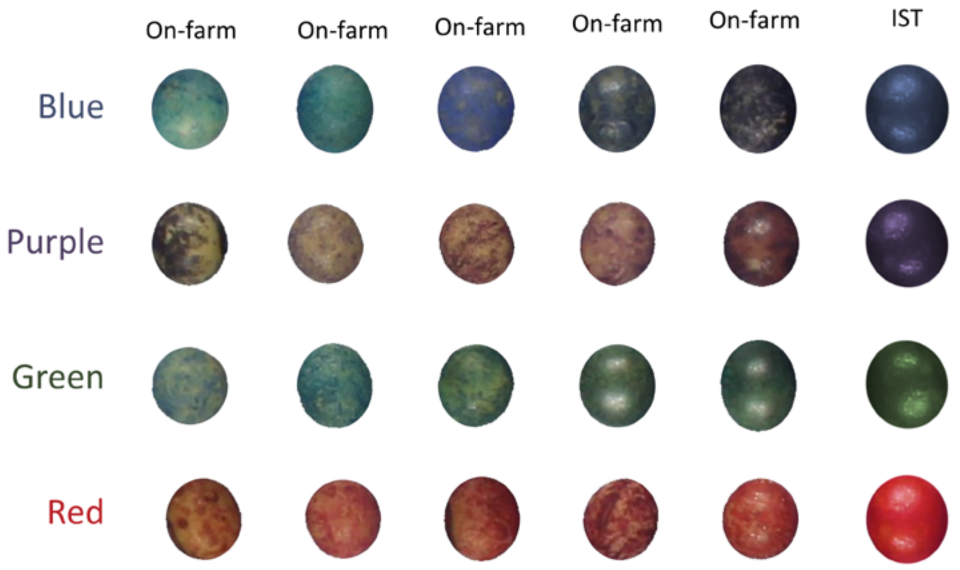

Figure 4. Coating of samples treated in predominant colors: blue, purple, green and red according to the application technologies on the farm (On-farm) and industrial seed treatment (IST).

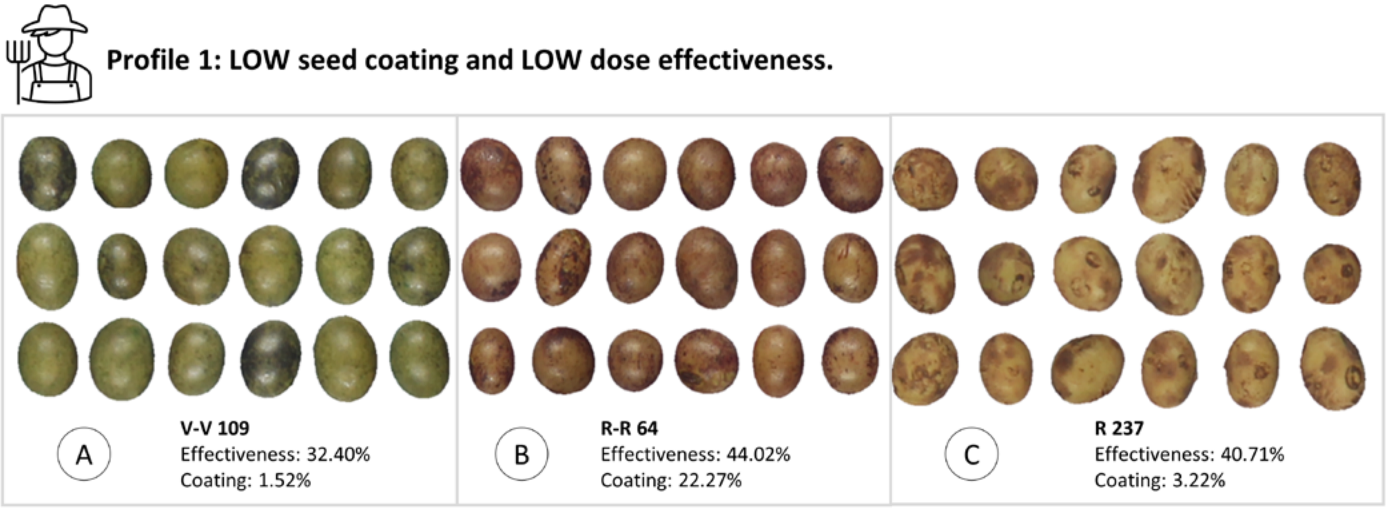

Figure 5. On-Farm samples with seeds with low coating and low dose effectiveness.

By means of other samples, it is possible to infer about the profiles of farmers who, in an attempt to improve the coating, significantly increased the dose applied in comparison to the recommended one, obtaining, however, a good coating. For example, with the samples V-R 60, V-R 18 and V-R 139 (Figure 7), this improvement may be linked to a more efficient primary application technology and/or the use of functional or other phytosanitary products to increase the spray volume.

There were samples in which the treated seeds showed high effectiveness of the dose of the active ingredient, resulting in an effectiveness close to 100%, but with low coating identified through image analysis. Examples include the samples V-V 176, V-R 50 and V-R 26 (Figure 8). This fact may be related to the excessive use of water in the treatment solution, seeking to improve the distribution of the product. However, the color or coating was very light, making image identification difficult.

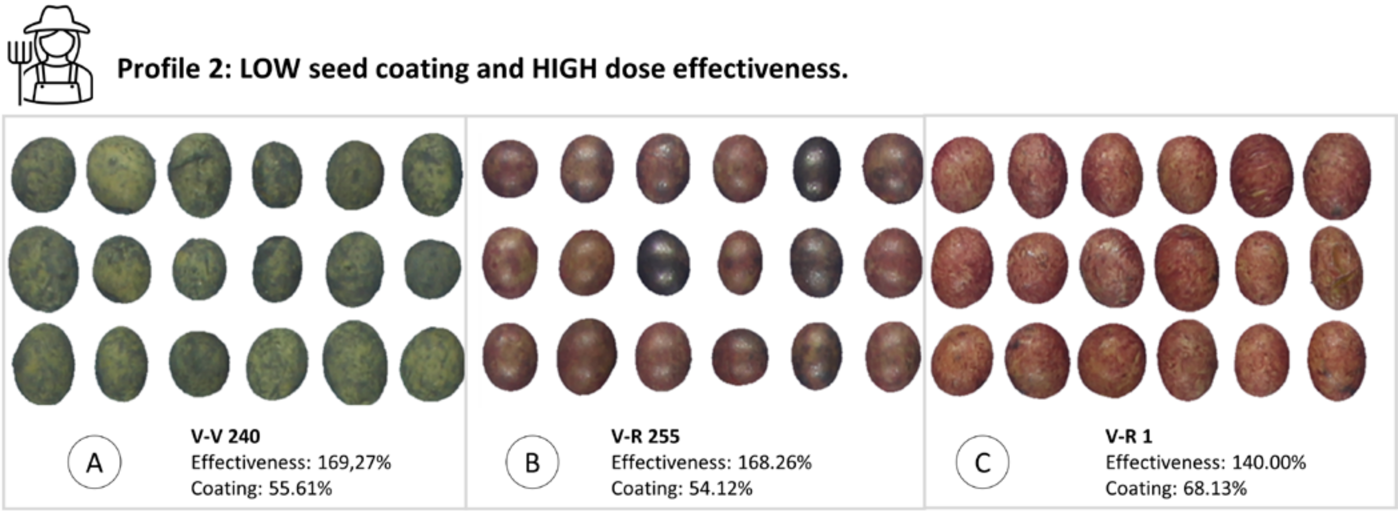

Figure 6. On-Farm samples with overdosing and low coating.

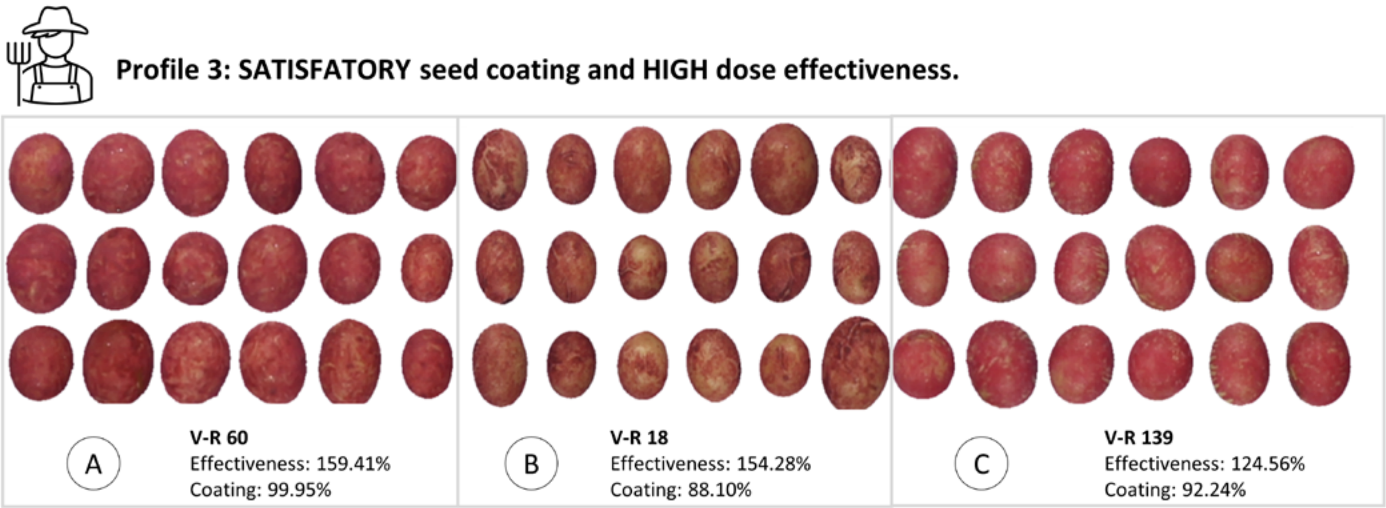

Figure 7. On-Farm samples with overdosing and satisfactory coating.

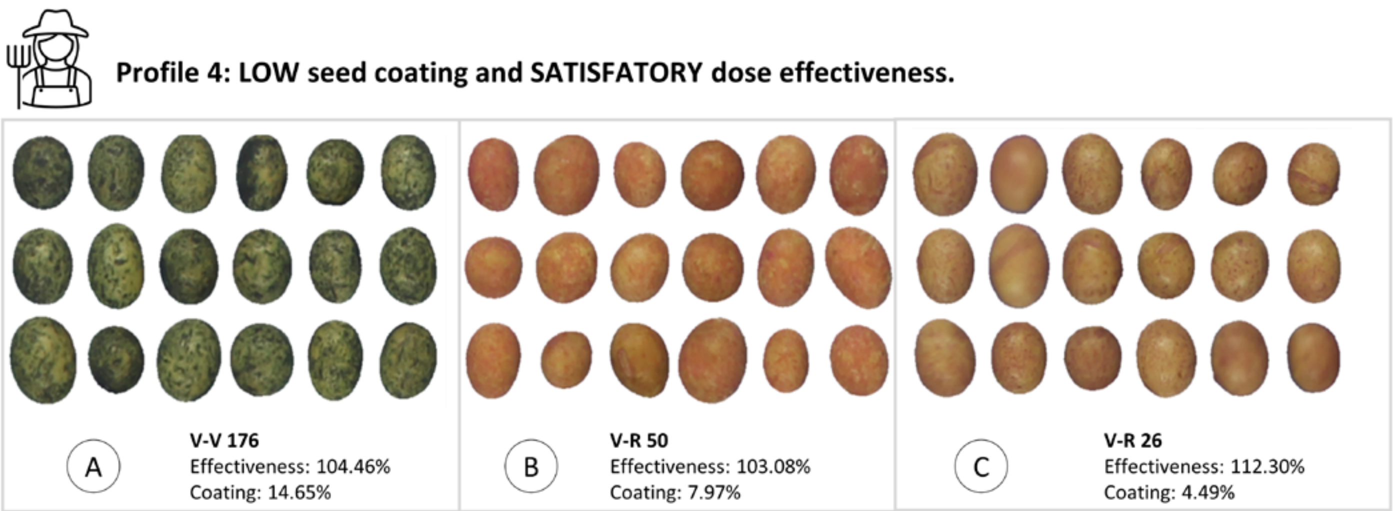

Figure 8. On-Farm samples with satisfactory dose effectiveness, but with low coating.

Samples with 0% effectiveness and coating results were those for which farmers reported the use of a phytosanitary product, but the active ingredient was not found in the samples. This means that the seeds have not been treated with the pesticide informed by the farmer, indicating a serious failure in the application of the product or the use of products of dubious origin or manufacture. Examples are the samples V-V 170, V-R 169 and R-R 182 (Figure 9).

Some On-Farm samples followed the quality standard of IST samples, such as V-V 55, V-V 69 and V-R 124, which showed effectiveness and coating close to 100%. This indicates that some farmers have application technology and technical assistance for an adequate seed treatment, even when performed on the farm (Figure 10).

Most of the IST samples collected showed seed coating and dose effectiveness considered satisfactory or classified as excellent, as exemplified by the samples V-R 21, V-R 100 and V-R 138 (Figure 11). These results are a consequence of better technology for the application of plant protection products and the use of functional products, such as polymers, associated with appropriate technical assistance.

Regarding the mean coating of all samples, the difference in the quality of the final treatment between IST and On-Farm was evident, with the mean value being 96.32% for IST samples and 66.39% for On-Farm samples (Figure 12B). This reinforces the discussion about the disparity in quality between application technologies. According to Andrade et al. (2024), the classification for coating is excellent in IST samples and low in On-Farm samples.

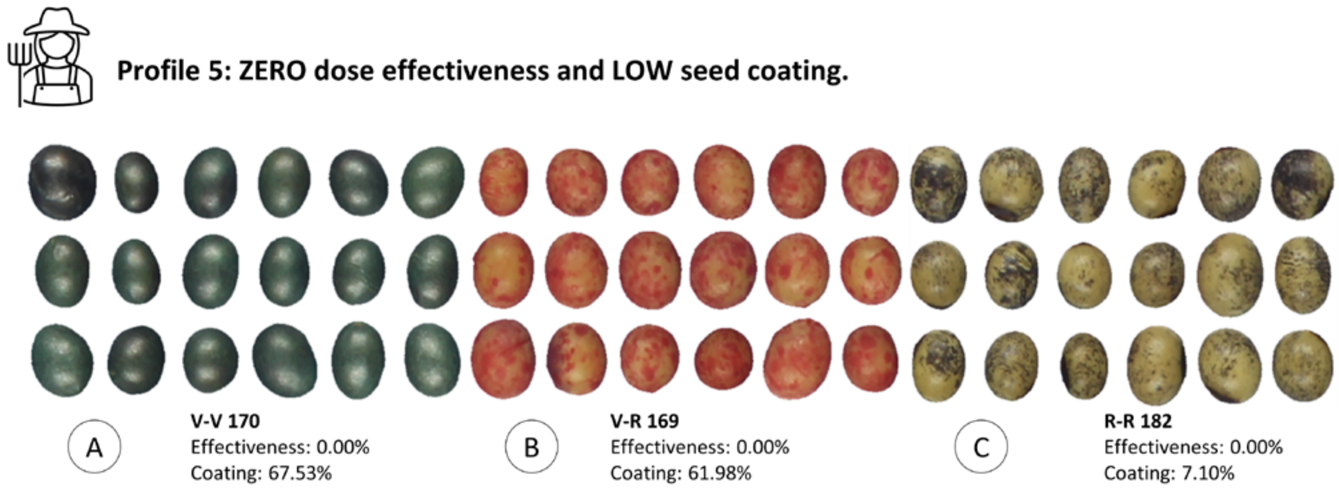

Figure 9. On-Farm samples with no dose effectiveness, but with coating.

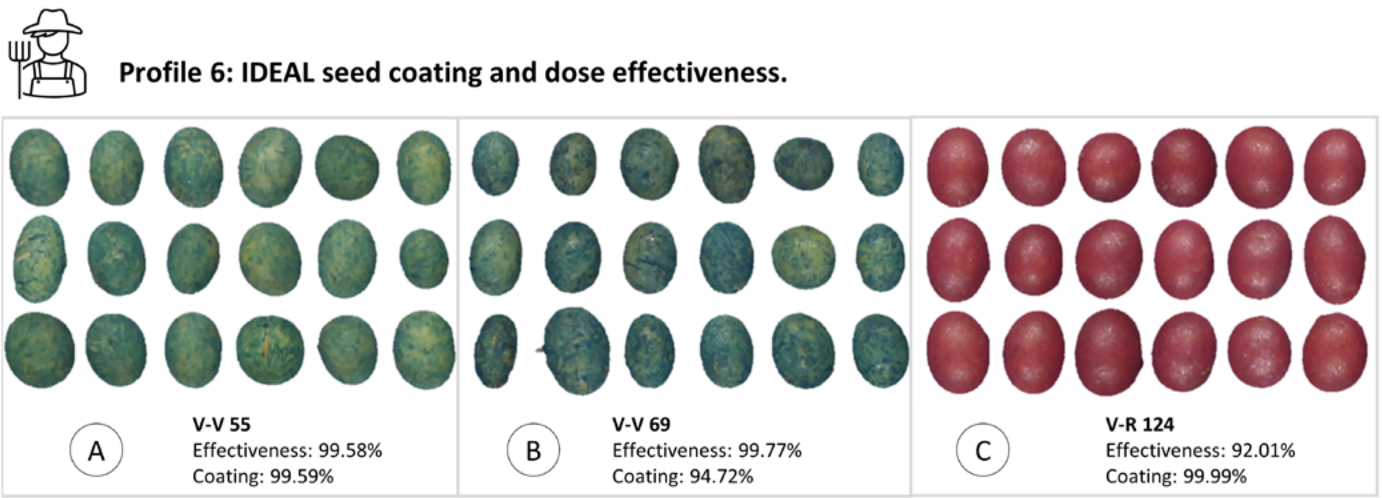

Figure 10. On-Farm samples with satisfactory dose effectiveness and seed coating.

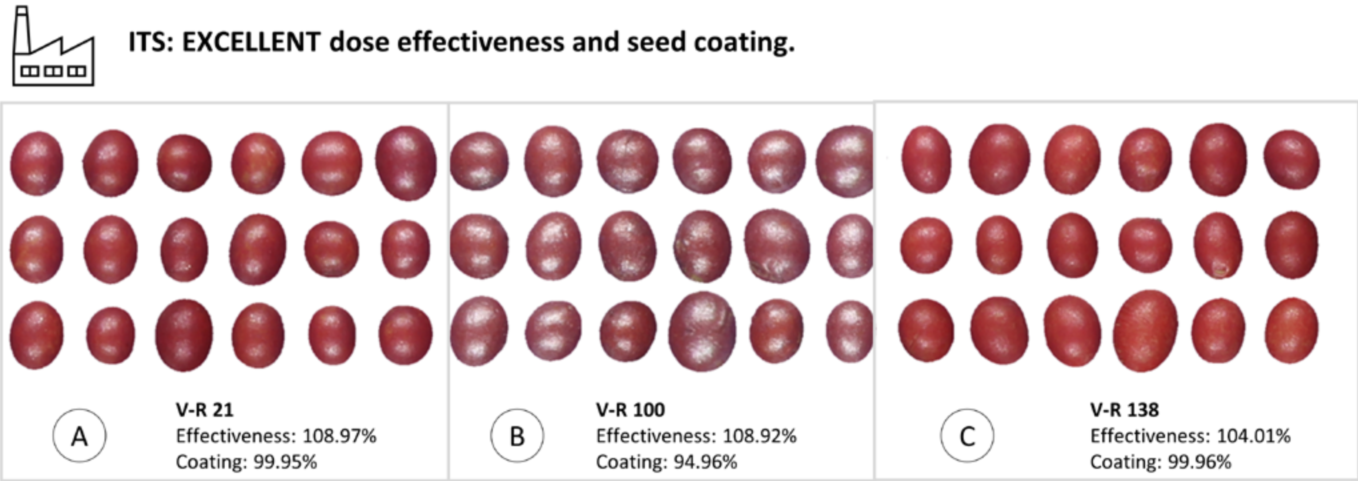

Figure 11. IST samples with excellent dose effectiveness and seed coating.

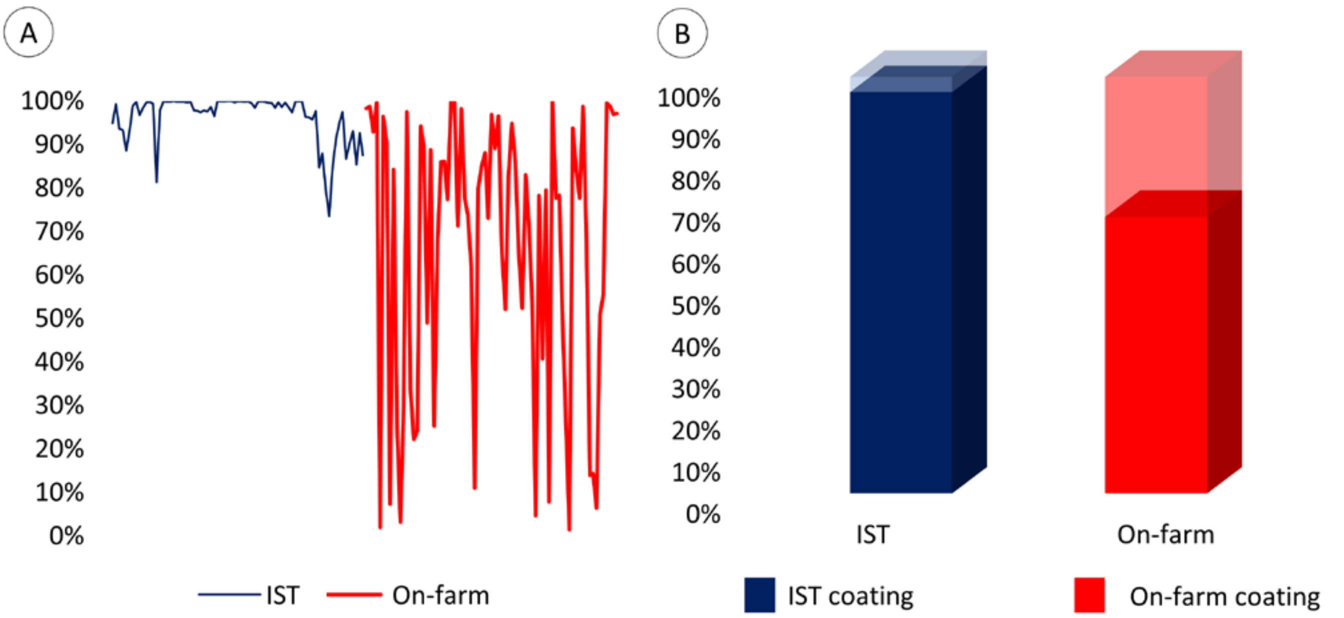

Figure 12. (A) Coating (%) of industrially treated samples (IST) and On-farm treated samples (On-Farm). (B) Average coating (%) of industrially treated samples (IST) and On-farm treated samples (On-Farm).

One of the problems found in the evaluations of On-Farm samples was the great heterogeneity among them regarding treatment quality, highlighted in the graphic representation of Figure 12A. Marked oscillations are observed for seeds treated on the farm, highlighting the lack of homogeneity in the technology of product application, with considerable variability among farmers. In contrast, for IST samples, subtle oscillations were observed for coating percentage, with most samples showing values close to 100%.

This result suggests that the failure can be attributed to technology and care during seed treatment, and the IST modality was superior. IST consists of the optimization of the primary application, which is the initial contact of the pesticide with the seed; when carried out incorrectly, it results in inadequate distribution of the products in the secondary application, which consists of the redistribution of the product seed by seed over the entire volume of the seed during mixing in the seed treatment equipment (Afzal et al., 2020). It is worth noting that there are exceptions, with farmers who are able to carry out On-Farm treatments with the necessary quality.

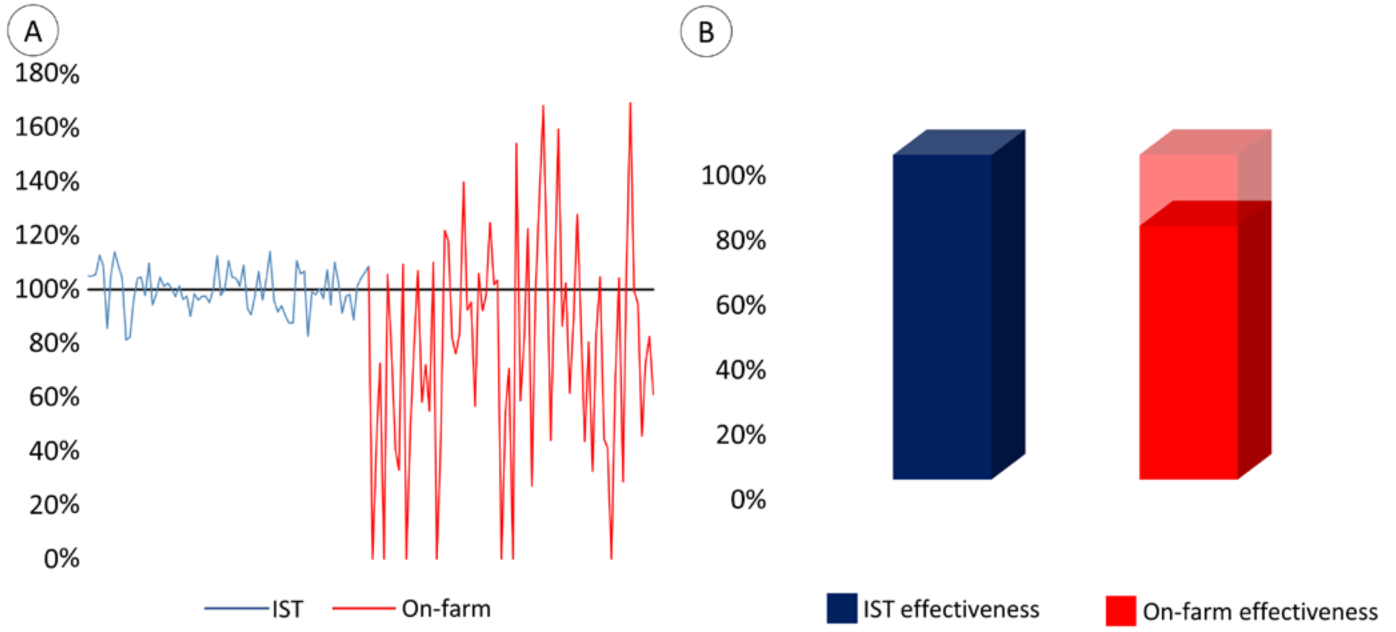

Figure 13. (A) Dose effectiveness (%) of industrially treated samples (IST) and On-farm treated samples (On-Farm). (B) Average effectiveness (%) of industrially treated samples (IST) and On-farm treated samples (On-Farm).

Regarding dose effectiveness, there was a small oscillation in the results of IST samples compared to On-Farm samples (Figure 13A). The average dose effectiveness was 99.96% for IST and 85.33% for On-Farm, highlighting the discrepancy in relation to dose effectiveness in the samples (Figure 13B). The heterogeneity of the results for On-Farm samples was higher than that observed in IST samples, and in general, the trends of results between coating and dose effectiveness were similar.

In this context, it is highlighted that when treating seeds in the industry, the applied technology optimizes the use of products, ensuring dose effectiveness and coating, due to the homogeneity of the treatment. On the other hand, in the samples treated on the farm, heterogeneous results were observed in terms of quality, indicating potential negative consequences resulting from errors in the dose, both due to underdosing and overdosing.

CONCLUSIONS

The use of blue background is the most appropriate for capturing and contrast in the images, promoting efficiency in their analysis to quantify the coating of treated soybean seeds, regardless of color dominance.

The use of high-resolution computerized image analysis is efficient to evaluate the quality of the coating of treated soybean seeds.

Coating of seeds treated in the IST modality is directly related to dose effectiveness.

Soybean seeds treated in the IST modality show a greater tendency and predominance of samples with high quality and homogeneity of treatment compared to On-Farm, exhibiting adequate coating and dose effectiveness.

On the other hand, seeds treated in the On-Farm modality showed heterogeneity in treatment quality, with considerable variability in coating and dose effectiveness.

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