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Techno-Economic Analysis for the Coating of Seeds with Sodium Alginate Plasticized by Glycerol Using the Wurster Fluid-Bed Bottom Spray Process †

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Abstract: The seed coating with sodium alginate plasticized by glycerol was simulated in batch mode using SuperPro Designer 10. The effect of changing certain inputs such as the seed size, film thickness, and the price of the seeds on the capital and operating costs was estimated. The process simulation predicts capital costs of EUR 250,000 and annual operating costs of EUR 730,000 for producing 1788 batches of 50 kg of coated seeds with a coating thickness of 50 µm for seeds with a diameter of 6 mm at an initial purchasing price of 5 EUR/kg. The annual operating time is considered to be 8000 h.

Keywords: process simulation; seed coating; techno-economic analysis

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1. Introduction

The Wurster coater was developed in the 1970s [1]. The historical use of the Wurster coating process was in the pharmaceutical industry [2–4], where only small amounts had to be applied to with respect to desired doses, and the added value was sufficient [3].

The Wurster fluid-bed coating process can be seen as an overlap between fluidized bed technologies and classical coating technologies [5]. The classical situation involves a circulation of the coated units (tablets, pellets, grains, seeds, etc.) that is facilitated by the continuously developing fluid bed [5–7]. Therefore, the fluid bed is continuously moving up the Wurster tube where fluidization occurs until it clears the tube into a new area where the fluidization conditions are not met since the diameter is abruptly changed. This causes the coating units to fall back at a level lower than the Wurster tube where they become the feed for the Wurster tube and begin a new fluidization cycle. As the coated units pass through the tube, the coating solution (containing the coating ingredients) is sprayed on the units inside the tube [5–7]. The critical part of the process is to achieve drying conditions synchronized to the fluidization conditions [6,8,9]. Process optimization also involves the coating solution properties in terms of the viscosity, vaporization enthalpy, and surface tension [10,11]. The coating ingredients also need to have specific mechanical properties when dried, which are good enough to resist the unavoidable collisions in the coater [12]. This is true especially for the Wurster process.

Seed coating (in its classical form) is a rather old practice that was attempted in many forms with a focus on pest control [13–15]. Seed coating was later developed as a way of ensuring a beneficial microbial presence in the rhizosphere [16,17]. Later, other applications were developed specifically that mainly consisted of coatings to resist diseases or pests with organic compounds aimed at reducing the effects of various pathogens [18–21]. Some of these organic insecticides were shown to have negative effects on pollinators (bees), which is in fact counterproductive [21,22].

Seed coating with natural compounds was also developed, and the best solutions aimed to find compounds that could have the right mechanical properties in order to coat, good physical integrity, and biodegradability. Biopolymers fit exactly into that category mostly because of their mechanical properties [23,24] but also their intrinsic properties as antifungal, antiviral, or biostimulants [24]. The most important results have been achieved with sodium alginate [25], chitosan [26,27], and pectin [28].

The coating process using biopolymers as a coating base and applied using the Wurster process has been less studied [8]. Techno-economic analyses are relevant when developing new technologies in order to assess economic feasibility. The predicted utility is also relevant but has be assessed together with expected capital and operational costs in order to have a clearer image of the discussed process. SuperPro Designer 10 is a software that simulates the technological and economic aspects of a process, predicting the optimum scheduling of unit operations and equipment occupancy in a batch-type process [29].

In the current study, a simulation was developed in SuperPro Designer 10 to evaluate the effect of the seed size, the required coating thickness, and the initial cost of the seed raw material on the costs of developing a seed coating facility and the inherent operating costs.

2. Methods

The methods involved in this work are described below. They include the proposed process simulation in SuperPro Designer 10, a statistical model developed to describe the effect of three different inputs on the coating mass, the capital costs, and the operating costs to produce a batch.

2.1. Process Simulation

A process simulation in SuperPro Designer 10 was developed containing three sections. The flow scheme is shown in Figure 1 with the three sections highlighted by three different colors. The first section deals with the coating process, the second section describes the crosslinking with $CaCl_2$, and the third section adds a packaging and labeling of the coated crosslinked seeds. The simulation was run in batch mode. With an annual operating time of 8000 h, the forecasted number of produced batch counts was 1776 batches.

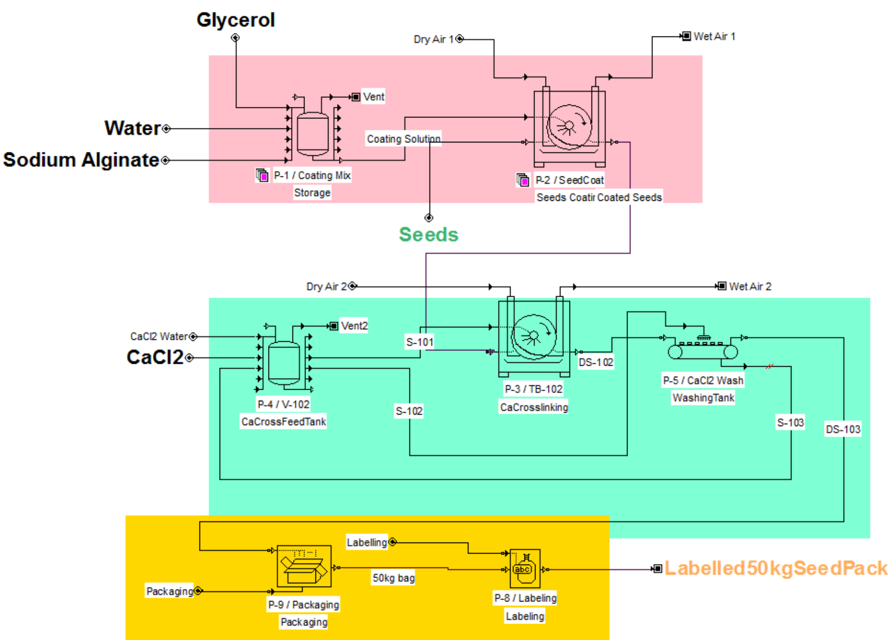


Figure 1. Overview of the process simulated using SuperPro Designer 10.

In the first section, the coating solution was first obtained by mixing in water, sodium alginate, and glycerol, such that the final solution was a 2% solution of both sodium alginate and glycerol in water. In terms of the order, water was added first, followed by glycerol, and alginate. The quantities per batch vary as they are related to the coating quantity requested by the coating unit in which the resulting solution becomes a feed. The mixing tank is priced at EUR 10,000 and has a fixed volume of 100 L. After three charge operations starting with the water stream, followed by glycerol and sodium alginate, the added ingredients were mixed for 2 h. The transfer into the coating unit was synchronized with the coating process. The coating process was performed with 50 kg/batch of seeds formed from a declared unit of 1 kg of seeds. This quantity was charged into the coating unit right before the coating process, which happens at 40 °C, taking 2 h or more depending on the desired amount of coating. The coating unit has an estimated price of EUR 30,000 and a volume of 100 L. After the coating process was finished, the coated seeds were taken to the next section.

In the second section, the initial calcium chloride solution was prepared simultaneously with the coating solution in section one so that it was ready immediately to be applied to the coated seeds. The solution had a concentration of 15% $CaCl_2$. Using such a concentrated amount is useful to maximize the rate at which the crosslinking is supposed to occur. The crosslinking reaction between sodium alginate and calcium is also very fast with respect to process times, even if it becomes controlled by diffusion as more calcium ions need to cross the already formed alginate gel. However, apart from maximizing the crosslinking rate, using a concentrated solution to wash the coated seeds is also very useful, as lower amounts of water are required to be dried after crosslinking. The SuperPro Designer 10 does not provide a type of unit that can simulate reactions between discrete (individual items) streams and bulk streams. We developed a work around this by employing an equivalent sequence of a coating process (which soaks the discrete batches, with some evaporation to simulate the drying of crosslinked seeds) and a washing step, which apparently removes the excess water and $CaCl_2$ and returns it to the crosslinking solution tank described before. This generates a loop which can simulate the return of the washing solution to the mixing tank at the end of one batch and right before the next batch. In terms of process scheduling, this shows that the feed solution at 15% $CaCl_2$ can be prepared at the same time as the coating solution. The mixing of the solution was estimated to have a price of EUR 1000 and the washing equipment to have a price of EUR 1000. The amount of $CaCl_2$ required for each unit of 1 kg of seeds was estimated at up to 10 g or 1% with respect to the proposed unit size.

In the third section, the coated and crosslinked seeds were packed and labelled.

In the cost model used by SuperPro Designer, the total equipment purchase cost is estimated from summing the listed equipment purchase cost and the unlisted equipment purchase cost (estimated as 20% from the total equipment purchase cost). The direct fixed costs are estimated as double the total equipment purchase cost. Operating costs are estimated for each individual piece of equipment.

2.2. Statistical Model to Evaluate the Effect of the Input Data on the Costs

We propose a simple model below, which relates the size of a seed (defined by its diameter) and the coating thickness to the total coating mass of 50 kg of seeds. This approach is meant to describe the domain of seed sizes and required coating thicknesses and relate them to the total coating mass. The seed is defined to be a perfect sphere with a uniform density of 0.75 g/cm^3. The film is assumed to have a density when dried of 1.2 g/cm^3 [8].

$$m_{coating}\left[\frac{\text{g } of\ film}{\text{kg } of\ seeds}\right] = \frac{m_{film}}{m_{batch}} = \frac{\rho_{film}\cdot A_{seeds}\cdot \delta}{V_{seeds}\cdot \rho_{seeds}} = \frac{\rho_{film}}{\rho_{seeds}}\cdot\frac{2\cdot\delta}{d} \tag{1}$$

Equation (1) is used to calculate the theoretical mass of the coating necessary to achieve a coating thickness of δ on seeds of diameter d. The value is expressed relative to one kg of seeds. The assumption that the coating volume can be calculated as the product of the specific surface and the coating thickness is a simplified one that is valid only when δ << d and also when δ < 100 μm, which gives a maximum relative error of 5% on the approximation (Figure A1).

The simulation was run at three levels for each of the three varying inputs presented in Table 1, namely the diameter of the seed, the coating thickness required, and the price of the seed. The evaluated domain is meant to explore the capital and operational costs for seeds of different sizes, which are hypothetically required to be coated with different thicknesses. The price of the uncoated seed raw material is also varied.

Table 1. Domain limits to explore the effects of seed size, coating thickness, and seed price on the capital and operational costs.

	Min	**Med**	**Max**
F1: Size of seed/diameter (mm)	2	6	10
F2: Min. coating thickness (μm)	20	50	80
F3: Price of seed (EUR/kg)	3	5	7

3. Results and Discussion

The SuperPro Designer 10 software is helpful to optimize the scheduling of different operations on different pieces of equipment to maximize the equipment use for maximum productivity.

The overall scheduling of the equipment use is shown in Figure 2 by describing the sequence of operations in each piece of equipment and how operations in different pieces of equipment can overlap (if possible) to maximize the equipment use.

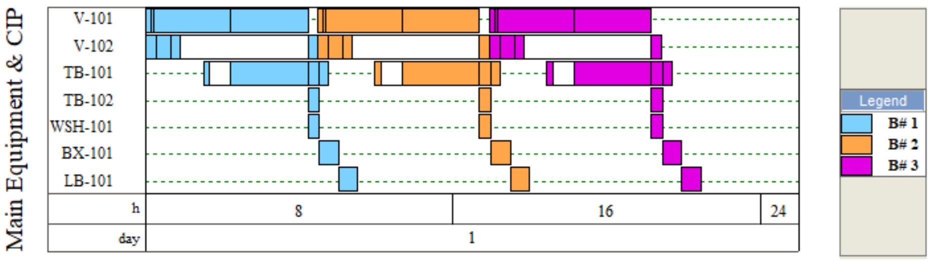


Figure 2. Scheduling of the equipment use in a sequence of three batches using SuperPro Designer 10.

The simulations were run 27 times to assess the three factors at three different levels. The values of the levels for each factor are given in Table 1. The minimum, medium, and maximum values of the response variables are shown in Table 2. This shows that changing the values of the input variables produces a smaller or a larger effect on the response variables. The changes in capital costs are related to the unit use. For example, if a larger coating thickness is required, the software automatically calculates the number of units required to correctly represent the production levels since this is proportional to the total coating mass required.

Table 2. Interval of simulated capital and operational costs.

	Min	**Med**	**Max**
R1: Coating mass (g)	26	269	512
R2: CapEx (EUR)	232,207	385,314	538,420
R3: OpEx (EUR)	544,836	815,281	1,085,726
R4: OpEx (EUR)/batch	301	456	611

Figure 3 is shown below and it contains four illustrations, which describe the four response variables influenced by the three input variables shown in Table 2. The two response surfaces in Figure 3a,b are actually represented with three surfaces so as to integrate their change with respect to the third factor, which is in both cases the price per kilogram of seeds (EUR/kg). The price of the seeds has a minimal effect on the capital costs. The small increase in capital costs is an effect of the changing working capital as the input seed price increases. The operating costs are most significantly influenced by the change in the price of the input seeds and depend minimally on the size of the seed and the minimum required thickness. Figure 3c relates the operating costs per produced batch of 50 kg coated seeds to the three factors.

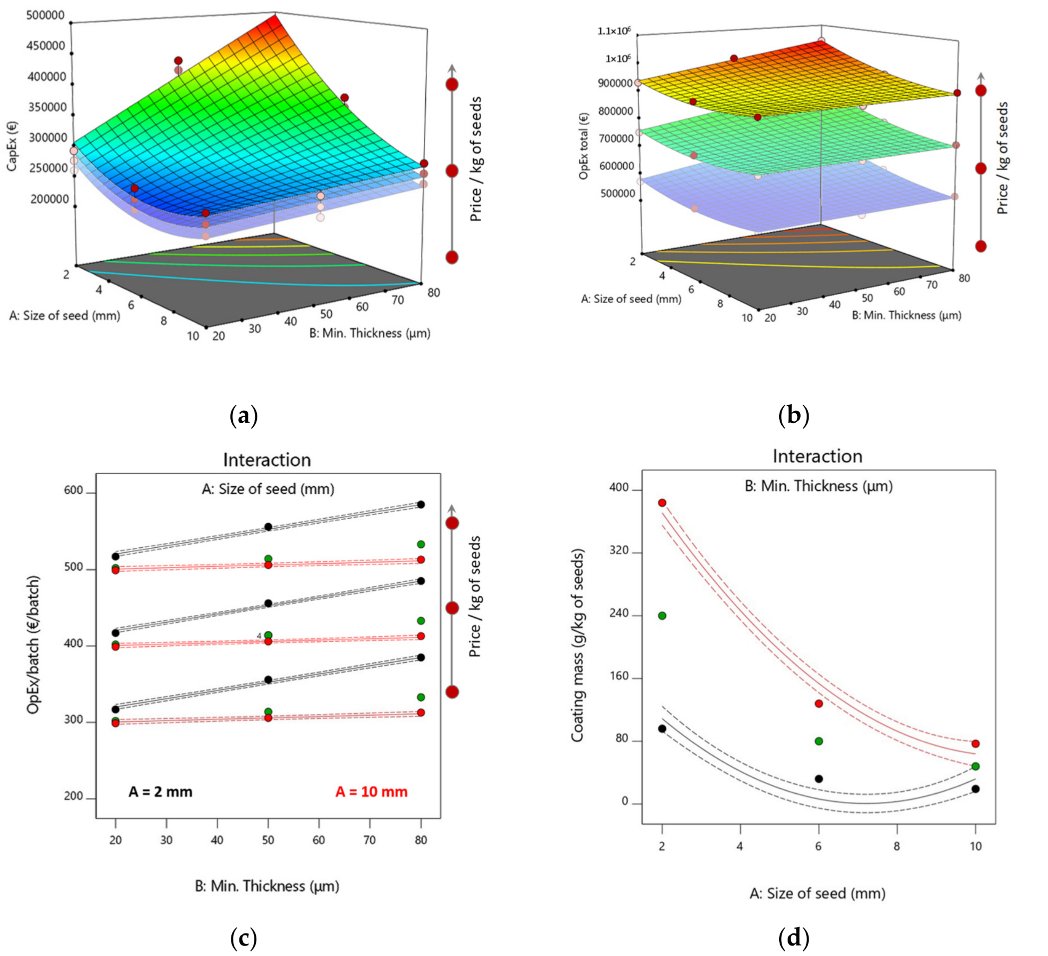
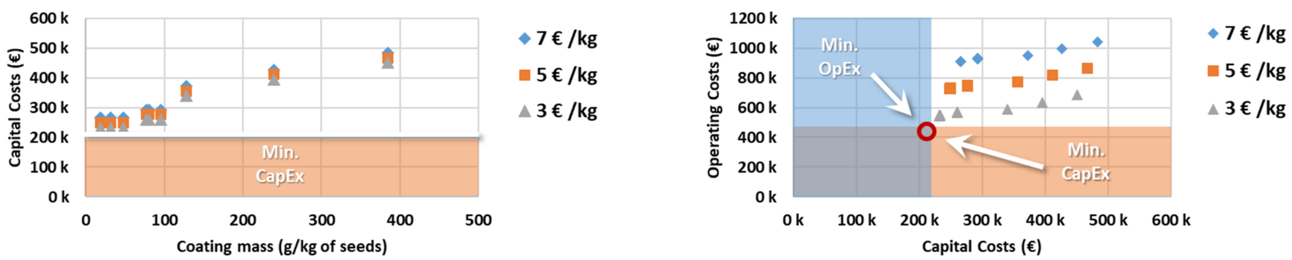


Figure 3. (**a**) The response variables as a function of the input variables: capital costs/CapEx; (**b**) operation costs; (**c**) operation costs per package of 50 kg of coated seeds at required thicknesses; (**d**) coating mass per kg of initial seeds.

While the price of seeds introduces a predictable linear effect on the OpEx/batch estimation, the two other factors affect the value as main factors but also due to their interaction term. Explicitly, the change in costs is small for seeds of different sizes at a 20 µm applied coating but becomes quite significant for a thicker coating. This is an effect of the higher specific surface of smaller seeds when compared to larger seeds. The change in the coating mass required is represented in Figure 3d. This is a complete representation of the domain described by the limits of the seed size and the required thickness values, which were imposed for the simulations. This behavior is in good agreement with the dependance given in Equation (1) of the mass coating/kg of seeds required, which is proportional to the ratio between the doubled required thickness and the diameter of the seed. It is important to note that the change in the required coating mass has a large impact on the capital costs since it is proportional to the required processing time but affects the operating costs very little, which are mostly affected by the price of the input seeds.

The simulated data presented above, namely the response variables can also be cross-correlated to give more information on the economic aspect of the process. In Figure 4a, the cross-correlation of the coating mass and the capital costs is represented. It shows that up to a coating mass of 100 g/kg of seed the capital costs are relatively uniform and are up to EUR 300,000, after which the capital costs increase more significantly. This is an effect of the multiple units required to achieve the desired production; in some sense, it increases stepwise as the simulation suggests, with the increase in the number of units for any given operation. Since the units hold operations that change differently with respect to the coating mass, the overall effect of the discrete increase becomes more and more even. At some point, although not be discussed in this work, the estimated capacity of each unit has to be increased to increase the processing efficiency. Figure 4b represents the cross-correlation between the operating costs and the capital costs for all simulations. This shows that the operating costs increase somewhat linearly to the capital costs for all seed sizes and required coating thickness. Of course, the input seed cost has a higher impact on the operating costs since it is the main raw material. Capital costs are not as influenced. However, overall, Figure 4b shows that the proposed process has a high OpEx with low CapEx. It also shows that the proposed process has high versatility with respect to the seed coating since the same investment can be used for different type of seeds.



(**a**) (**b**)

Figure 4. Cross correlation for all the simulated capital costs and coating mass (**a**) and all the simulated capital costs with operating costs (**b**).

The results presented above only discuss the effect on costs (capital or operation) for seeds of varying dimensions coated with varying amounts of the sodium alginate/glycerol film. In terms of profitability, the added value of the coating needs to reflect the added utility. The cost components in the modern era can contain many items such as fertilizers, other chemicals, irrigation, etc. The value added by the coated products has to lead to a reduction in the costs in these cost categories. This subject is very specific for each type of seed and can be relevant in certain situations but provide no added utility in other situations. For the sodium alginate/glycerol system, the utility is generally derived from an added retention of water or a biostimulant effect that maximizes seed germination and initial growth, which can lead to an overall increase in crop productivity. Alternatively, this system can also be used as a delivery system in which other useful compounds are introduced to facilitate the maximum seed germination and initial growth.

In the following paragraphs, the structure of the economic calculations simulated in SuperPro Designer 10 are described in detail. Figures 5 and 6 show the cost components simulated by SuperPro Designer 10 for the center point inputs (with respect to the chosen input intervals): seed input price/kg = 5 EUR/kg, seed diameter = 6 mm, required coating thickness = 50 μm.

Capital investment		
Equipment Purchase Cost	90000	€
Direct Fixed Capital (DFC)	180000	€
Working Capital	59819	€
Start-up and Validation Cost	9000	€
Up Front R&D	0	€
Up Front Royalties	0	€
Total Capital Investment	**248819**	€

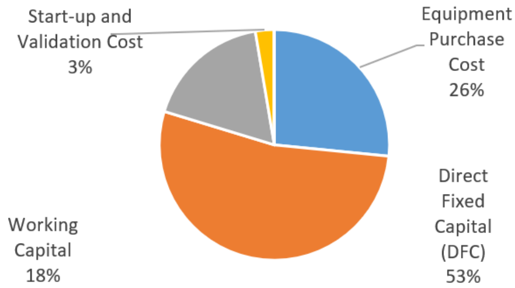


Figure 5. Cost components for the simulated total capital investment (seed input price/kg = 5 EUR/kg, seed diameter = 6 mm, required coating thickness = 50 µm).

Operating Costs		
Materials	492321	€
Facility-Dependent	42300	€
Labor-Dependent	165326	€
Laboratory/QC/QA	24799	€
Consumables		€
Utilities	2902	€
Waste Treatment/Disposal	0	€
Transportation	0	€
Miscellaneous	0	€
Other	0	€
Total Annual Operating Cost	**727647**	€

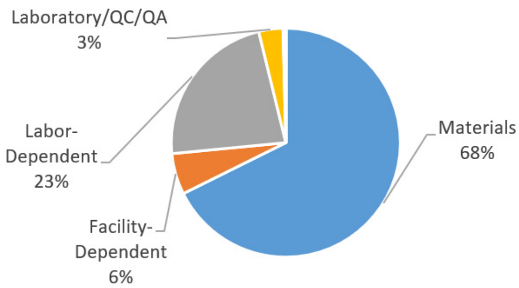


Figure 6. Cost components for the simulated operating costs (seed input price/kg = 5 EUR/kg, seed diameter = 6 mm, required coating thickness = 50 µm).

Figure 5 shows that the equipment purchases represent 26% of the capital expenditures, the direct fixed capital represents 53% and the working capital 18%. Start-up and validation costs represent the remaining 3%. The equipment purchase cost is estimated from the user-defined values of the main units. The start-up and validations costs are estimated as 5% from the direct fixed capital, which was approximated as double the equipment cost. The working capital is calculated by Super-Pro-Designer 10 and reflects the estimated costs to cover 30 days of labor, raw materials, and utilities.

Figure 6 splits the operating costs in its main components and shows that the materials represent 68%, facility-dependent costs are 6%, while labor represents 23%. Laboratory/QC/QA are estimated as 15% from the labor-dependent costs. Utilities are calculated at the standard consumption rates as estimated by the software.

4. Conclusions

Seed coating is a promising technology, which will likely be a part of future developments aimed at improving crop yield in an efficient and sustainable manner. Our work provides an overview of some of the economic aspects tied closely to technological insights.

In this study, the simulation developed in SuperPro Designer 10 predicts certain aspects related to unit operations and scheduling. At an annual operating time of 8000 h, 1788 batches of 50 kg coated seeds pack can be produced.

Three inputs relevant for a generic seed coating process are varied independently. A statistical model is developed that shows how the coating mass, capital, operation costs, and cost/produced batch vary depending on the seed size (2 to 10 mm in diameter), the required coating thickness (20 to 80 µm), and the price of the initial seed raw material (varied from 3 to 7 EUR/kg). In the established domain, the simulated capital costs vary from ~EUR 230,000 to ~540,000, the operating costs vary from ~EUR 545,000 to ~1,085,000 and the production costs per 50 kg batch of coated seeds from ~EUR 300 to ~600. The most important effects on the capital costs are the seed size, followed by the required coating thickness and their interaction term. The smaller the seed, the higher the mass of coating that needs to be applied per batch. The simulation predicts higher costs as a higher number of units of fixed volumes are necessary to process the higher mass of coating solution.

Coated seeds can have an impact on the current cost components in crop farm activities. However, the costs of production need to reflect the added value for the farmers in the reduction in other costs that maintain or increase crop production.

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Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

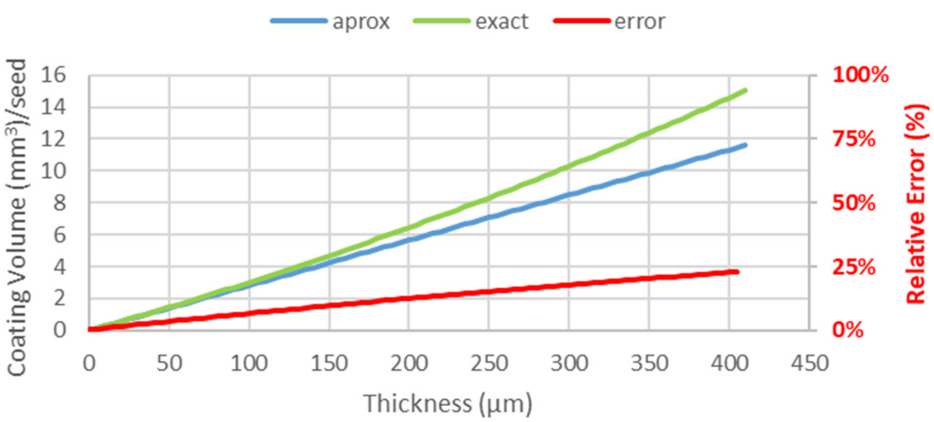

Figure A1. Theoretical coating volume applied to a spherical seed calculated using a simplified assumption valid when seed sphericity is not considered, the exact value that considers sphericity, and the relative error between the two.

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