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Sustainable technology for the production of artisanal cassava starch

Tecnologia sustentável para a produção de fécula de mandioca artesanal

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ABSTRACT

Yucca starch (*Manihot esculenta* Crantz) plays several important roles in agroecological agriculture in the tropics. It is an inexpensive source of carbohydrates of high nutritional quality and easily accessible, if preserved and stored. The process of starch artisanal extraction is carried out in Latin America in a rudimentary and impractical way, with water and raw material wasted, which generates losses and ecological problems. This study shows how a prototype of a technological process (Matilda v1.0) for the artisan extraction of yucca starch was designed, built, and optimized. The optimization was performed using the response surface methodology, and the experimental design is a Box-Wilson 2^3 full factorial central composite, uniformly rotated and orthogonally blocked per day. Around 60 kg of starch for 200 kg yucca on a working day was obtained. The estimated starch yield was 31.83%, within a confidence interval of (30.24-32.97%) and a prediction interval of (27.98-35.23%). This yield was higher than that reported for conventional artisanal extraction. Water use was about 0.3 L kg^{-1} yucca, significantly lower than in artisanal productions. The process developed would generate a lower impact on the environment and would allow small producers to empower themselves with sustainable technologies.

Palavras-chave:
Substituto de farinha
Farinha de amido
Projeto composto central
Tecnologia sustentável

RESUMO

A fécula de mandioca (*Manihot esculenta* Crantz) é muito importante na agricultura agroecológica tropical. É uma fonte barata de carboidratos de alta qualidade nutricional e de fácil acesso, desde que devidamente preservada e armazenada. O processo de extração artesanal do amido é realizado na América Latina de forma rudimentar e impraticável, com desperdício de água e matéria-prima, o que gera perdas e problemas ecológicos. Este estudo mostra como um protótipo de processo tecnológico (Matilda v1.0) foi projetado, construído e otimizado para a extração artesanal de fécula de mandioca. A otimização foi realizada usando a metodologia de superfície de resposta, e o desenho experimental é um composto central fatorial completo Box-Wilson 2^3, girado uniformemente e travado ortogonalmente por dia. Cerca de 60 kg de amido foram obtidos para 200 kg de mandioca em um dia de trabalho. O rendimento médio de amido foi de 31,83%, com intervalo de confiança de 30,24 a 32,97% e intervalo de predição de 27,98 a 35,23%. Este rendimento foi superior ao relatado para a extração artesanal convencional. O uso de água ficou em torno de 0,3 L kg^{-1} de mandioca, significativamente menor do que nas produções artesanais. O processo desenvolvido geraria um menor impacto ao meio ambiente e permitiria que pequenos produtores agrícolas se capacitassem com tecnologias sustentáveis.

INTRODUCTION

Yucca (*Manihot esculenta* Crantz) is a plant whose roots provide food and maintenance to more than 600 million people worldwide. This plant tolerates seasonal droughts and poor soils and has the incomparable ability to recover after stems and leaves have been affected by pests and diseases (DOMÍNGUEZ et al., 1983; ÁLVAREZ et al., 2002; PARMAR et al., 2017). Yucca is a very accessible crop in Venezuela where it is mainly used for fresh consumption and the production of flour and starch. It contains more starch by dry weight than any other food crop. This makes yucca flour, the ideal substitute of foreign products, such as wheat flour (ALARCÓN Y DUFOUR, 2012). These imported flours represent important currency expenditure for both the public and private sectors in our country and the rest of the world (CARTAY, 2004; ZAMBRANO Y SOSA, 2018; OLIVEIRA et al., 2019).

In different areas of industry, the gelling agents used for the preparation of crop media are costly and difficult to obtain, which delays the process of research and production of bio-inputs developed in Venezuela. This led us to search for a viable and low-cost alternative in the evaluation of starch as a gelling agent (MALIRO Y LAMECK, 2004; ROMAY et al., 2006).

Yucca starch is a natural polymer composed of 20-30% amylose (linear polysaccharide) and 70-80% amylopectin (branched polysaccharide). This particular combination and the nature of the starch components result in native rheological properties (viscosity, viscoelasticity, dispersion stability, etc.) which might suggest the use of yucca starch as a gelling agent. Although the extraction of yucca starch is achieved with simple and manual technologies, these are very laborious, using excessive water consumption and very low yield (ZHU Y XIE, 2018; NGNASSI et al., 2019).

In this research, a total of 73 bibliographic references was evaluated on the design of prototypes for the extraction of starch of plant roots, Musaceae, tubers, legumes, cereals, and other sources, both artisan and semi-industrial. Those prototypes were chosen when they met two or more of the following design criteria: low water use, manual traction, made with low-cost materials, compliant with the starch extraction process proposed by FAO, safe to the operator at the time of its use, and easy operate and maintain). Producers and artisans from different localities of Venezuela involved in artisanal starch extraction were consulted (ACOSTA, 2005; SARANRAJ et al., 2019). A summary was made including the most important ideas collected from the previous process. Then, the different works and experiences were considered, discussing the design parameters that should be met by the FAO grade technological process. With FAO grade, we want to point out that the quality of the starch obtained meets the standards of the Codex Alimentarius (FAO &WHO, 1995). After exhaustive reviews, preliminary designs of machines in freehand sketches were carried out; these drafts met the criteria of the technological process of yucca starch extraction (ACOSTA, 2005; BELLO-PÉREZ et al., 2006; SHITTU et al., 2016)

This study describes the design, construction and optimization using the response surface method of an artisanal technological process (Matilda v1.0) that allowed the production of cassava starch at low cost and with easy operation and maintenance. As a result, not only a substantial saving of water used in the production of starch is achieved, but also the yield above the artisanal average reported by the FAO for obtaining cassava starch under rural conditions.

MATERIAL AND METHODS

Design, technical memory, and construction of the technological system for the extraction of yucca

For the design of the technical proposal, the project management methodology was used (YOUNG, 2007). The technical project described:

The technical problem: the artisanal extraction process of starch is carried out in a rudimentary and impractical way, where the use of resources such as water and raw materials are not very efficient, generating economic losses. This represents an ecological problem due to the abundance of waste produced;

The prior technical proposal: after the exhaustive described review, several sketches or preliminary designs that were framed within the pre-established criteria were specified. We discarded those that did not comply with the technical and economic feasibility. Prototypes were built from the definitive preliminary design for their proof of concept. Subsequently, the final preliminary design was chosen, and the construction plans were created using FreeCAD v0.15 software (FREECAD, 2015);

The general report: consisted of a final technical proposal which set out the entire essential factors that the technical project must solve. A preliminary draft was made, accompanied by drawings (sketches), which included all the suggested indications. A descriptive report was prepared including the final solution chosen, materials to be used, the process followed for the construction of the prototype, approximate cost and handling of the prototype. Finally, the CAD isometric plans of the final solution were made;

General plan: a general plan was designed that showed the general dimensions of the technical system chosen as a solution. This was done through bounded views (raised, planted, profile), which allowed us to obtain a simple and clear drawing as much as possible.

Also, a general plan was elaborated that showed the different pieces that made up the machine and the relative location of each of them. A view of the whole machine was made and using tags to identify its parts. For both, the set and each of the pieces that made up the machine, a diagram was made where the technical characteristics of each piece and their manufacture were reported: Measurements of each piece in mm (information obtained from the general drawing); Material with which the piece was to be manufactured (information extracted from the previous definitive design); Number of pieces to be made (information extracted from the assembly plane); Final type, color.

Performance tests of the "Matilda v1.0" prototype (extraction, work, and water use performances) at the different stages of the artisanal extraction of yucca starch

Reception of the yucca roots: these were subjected to the starch extraction site as quickly as possible (about 24 h) after being harvested to prevent physiological damage or microbial deterioration, which might have lowered the quality of the starch;

Washing and peeling of the roots: at this stage of the process, any possible impurities of the roots after being harvested were eliminated. Yucca was weighed for each experimental block and placed in the washing and peeling machine (machine 1). Several tests were performed to estimate the best wash and hull weight. The optimal amount of water needed to perform this stage in the best way for the operator was also measured, that is, with the maximum load of water and cassava roots in machine 1 that would allow handling without difficulty and easy operation;

Grating of the roots: this stage was carried out with a rotary grater (machine 2) with a diameter of 35 cm, an area of 110 cm^2, holes of 1.2 mm in diameter with 2 perforations per cm^2, and a density of 594 holes/cm^2. Each load (kg of washed and peeled yucca) and the grating time were evaluated to standardize this stage;

Sieving and starch extraction from yucca root grinding: this process was intended to separate the fiber from the yucca root that would be deposited in the slurry (water + starch). The sieve was 59 cm wide by 62 cm long with a depth of 8 cm. Sieving time was a factor to evaluate in our response surface design;

Starch sedimentation: in this process, the objective was to decant the starch granules suspended in water. The optimum amount of water for sedimentation was also evaluated;

Starch drying: At this point, the aim was to eliminate the moisture contained in the starch up to 12 or 10%. This was done in the machine 3 (solar oven). The time of starch rotation and the drying time in the solar furnace were used as factors in our optimization design. The moisture percentage was determined according to COVENIN (1980) and FAO, WHO (1995). Three replicates were taken for each tray or treatment. Finally, in the precision stage, the difference between the results obtained for the two determinations of the same test was calculated and must not be greater than 0.2%. The yield was established through the percentage relationship between the weight of starch obtained and the weight of washed and peeled yucca used in grating in each treatment or tray. Finally, the conditioning of starch grinding, sifting, and packaging were completed (ARISTIZÁBAL et al., 2007).

Optimization of the yucca starch production process, using the technological process built

Once the best peeling and washing conditions of yucca and the optimal use of the water were determined, the extraction process was optimized, with emphasis on sieving and drying in the oven the starch obtained, following the response surface methodology (RSM) (BOX; WILSON, 1951; MONTGOMERY, 1986).

The RSM design was a complete factorial 2^3 (three factors and two levels) central composite Box-Wilson factorial design (DCC) blocked (per day), rotatable and orthogonal (α = 1.86). Factor 1 was the sieving time with 2 levels plus the zero point (20, 40 and 60 min; in coded units: -1, 0, +1); Factor 2 was the rotation of the material during drying and two levels plus the zero point (2, 3 and 4 turns, coded units: -1, 0, +1). Factor 3 was the drying time and the levels plus the zero point were 2, 4 and 6 h (in coded units: -1, 0, +1) (Figure 1).

The experimental design with the randomized arrangement of the runs, factors, blocks, and the response variables (% humidity and yield) are shown in Table 1. The test was performed in three blocks and 42 strokes (treatments) were carried out in total (14 runs per block). This design consisted of six replicates of the central point, eight factorial points with three replicates and six axial points with two replicates each. In this way, the experimental error was efficiently estimated for the design to be sufficiently robust. The estimated regression model of the DCC design was a second-order polynomial (Eq. 1).

$$Y_{123} = \beta o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \xi \qquad (1)$$

Where: Y_{123} is the experimental observation; X_1 is the sieve time of starch (min.); X_2 is the starch rotation time during drying (number of turns); X_3 is the drying time of the starch (min.); β's are the factor coefficients; ξ is the experimental error.

The β coefficients were estimated using the least squares method. The optimization was performed according to the method of the desirability function where the performance conditions are maximized. For the statistical analysis, the Design-Expert v7.15 (STAT-EASY, 2008) software was used under license 2155-6384-4138-EVAL. Each tray in the solar dryer was filled with equal volume until all the starch obtained in each sieving treatment was used (total of 6 trays per treatment). This way, each yield per tray was multiplied by 6 (Figure 2).

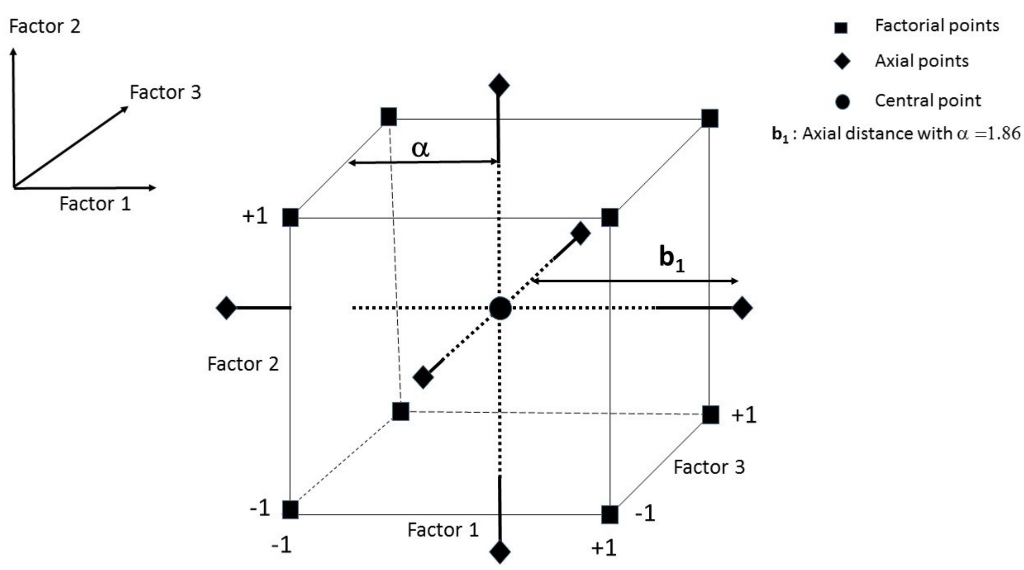

Figure 1. Graphical model of the DCC factorial design. The image shows the three factors to be evaluated, eight factorial points, four axial points and the single central point. b_1 represents the axial distance for α = 1.86.

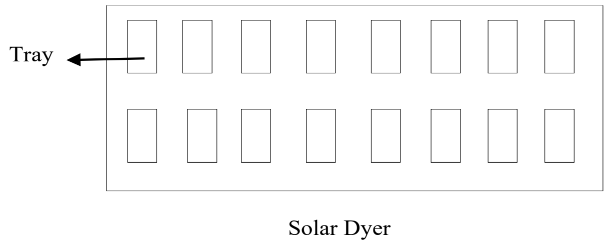

Figure 2. Diagram of the top view of the solar dryer showing the layout of the trays or treatments per block.

RESULTS AND DISCUSSION

After an exhaustive review of the literature and several preliminary tests, a technological process consisting of the MATILDA v1.0 prototype was developed (Figure 3). The process consisted of a series of coupled machines able to extract yucca starch under artisan standards and contemplating the following criteria.

Simplification of the artisanal yucca starch extraction process (ARISTIZÁBAL et al., 2007), concentrating several stages on one or at least two machines, complying with the standard described in the manual; manual operation; made with low-cost materials; showed an optimal management of the water resource; showed a good yield of starch production; low maintenance cost.

Table 1 shows the estimated performance for the washing and peeling stages as well as the grating of the yucca. The washing and peeling load were calculated by working time (6-8 hd^{-1}) resulting on a work capacity of about 200 kg of yucca per d and approximately 60 kg of starch was produced/d (maximum starch yield of 32%). This finding is above the *rallanderias* (artisanal starch Colombian producer). The use of water is about 0.3 $l\,kg^{-1}$ of yucca material. Significantly, this value was less than that of the *rallanderias*, who report a consumption of water up to 20 l/kg of yucca. In respect to the starch yield (32%), it is located at midpoint between the semi-industrial yield (40-50%) and conventional artisanal yield (17-20%) (ARISTIZÁBAL et al., 2007).

In summary, the developed system contemplates an efficient use of water that would benefit peasant communities where this resource is limited. Although the machines are of manual traction, a satisfactory working capacity was obtained that could serve small producers of yucca (productions of ¼ of ha). These producers represent a major part of Venezuelan and other Latin-American farmers, who do not usually have access to electric energy. We emphasize that, estimated starch production allows for the use of this product as a substitute for food-containing wheat flour. This increases the quality of life of farmers by assuring a better economic income and, at the same time, reducing dependence on imported products.

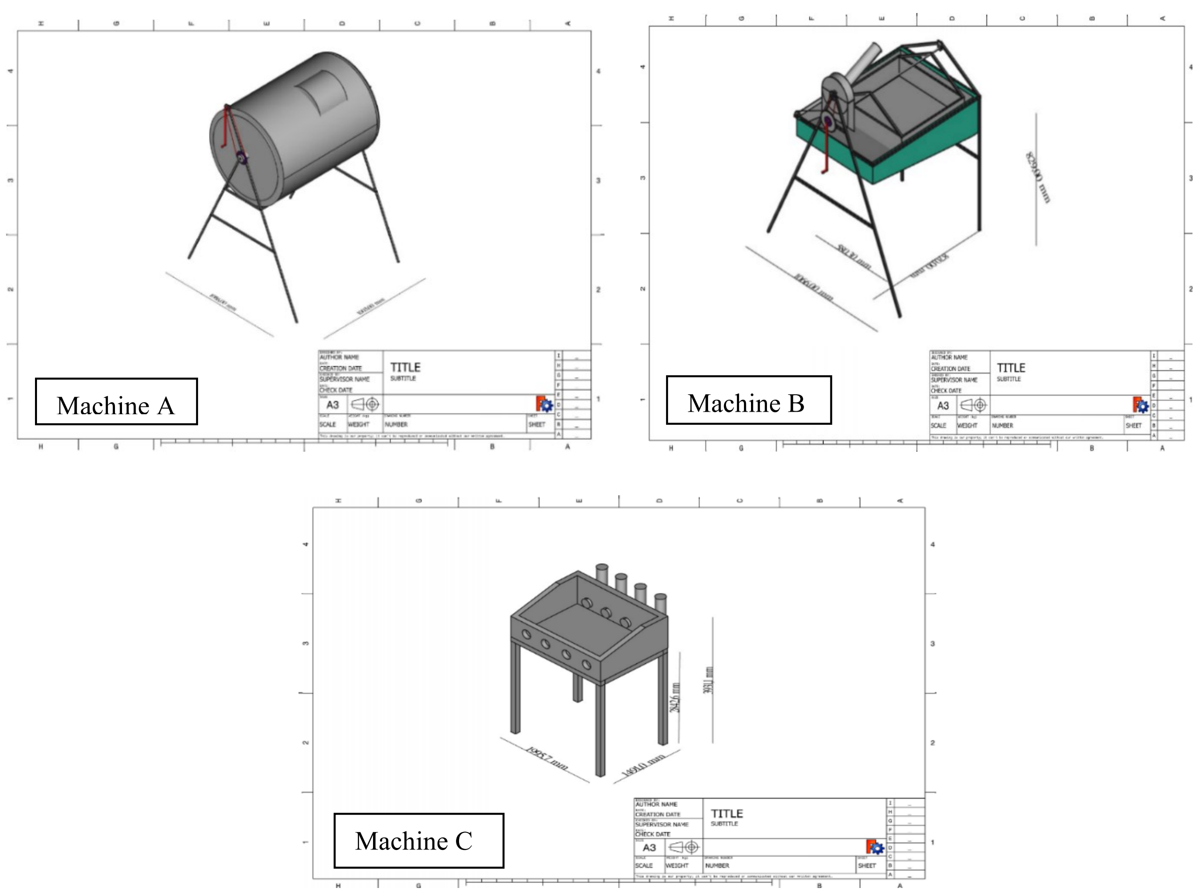

Figure 3. Isometric views of the designed technological process (MATILDA v1.0). (The three machines are shown and the explanation in the text). It was used FreeCAD v0.15 software (FREECAD, 2015)

Table 1. Performance summary for maximum workload for the designed technological process (MATILDA v1.0).

MCW/L Machine 1 (kg)	MVW Machine 1 (l)	WT/ML Machine 1 (min)	MCW/L Machine 2 (kg)	WT/ML Machine 2(min)	OVW/L Machine 2 (l)
10	5	10	10	20	30

MCW/L - maximum yucca weight/load to use in the machine; MVW - maximum volume of water/load to be used in machine; WT/ML - working time/maximum load on machine; OVW/L - optimal volume of water / load to be used in the machine.

Another important technical issue that must be approached in the future is the use of the by-products such as husk, husk bran and residual water for artisanal ethanol production and food formulation.

The moisture reached by the solar dryer was between 20.3 and 30%, and the starch yield was between 11.3 and 37.1, minimum and maximum, respectively. The 31.8% starch mean yield was estimated under the optimum operating conditions. The maximum required starch moisture of 12% could not be obtained due to adverse climatic conditions. For compute starch yield, required starch moisture was obtained using electrical oven.

For the moisture variable, the model was not significant and the determination coefficients were very low, which suggests this deficiency of the adjusted model should be explored in new experiments. One possible explanation would be that little variation was observed in the response variable (humidity) due to the climatic conditions under which the drying test was performed. For this reason, we propose to repeat these experiments to evaluate the humidity again ensuring that it is under appropriate atmospheric conditions.

In the case of the performance variable, in addition to the linear components, we observed the presence of quadratic terms and interactions type $X_1X_2^2$ (P<0.0001). The cubic term for the screening time factor, although significant, was removed since it was confusing (Figure 4). Additionally, the model meets the assumptions of normality, constant variance (homoscedasticity), and independence of the residues. Although no satisfactory drying was obtained, the yield variable was optimized including drying time and starch rotation. This was done because we considered certain interactions and quadratic effects to ensure hierarchical modeling.

The analysis of variance (ANOVA) (Table 2) showed that the estimated model for yield is statistically significant (P<0.0001) and the lack of adjustment was not significant with α = 0.01, suggesting that the model and the order of the polynomial were appropriate. The simple and adjusted coefficients of determination r^2 = 0.94 and r^2_{adj} = 0.92, respectively (the difference between the two should not be greater than 0.2) suggest that the model explained the variability present in the data in more than 90%. The precision value (Adeq. Precision) of 30.4 was sufficient to ensure an adequate model (Table 3).

Table 2. ANOVA for the response variable starch yield of the designed technological process (MATILDA v1.0)

Source of variation	Square Sum	Degree of freedom	Mean square error	*F*	*p*-valor	Statistical significance
Block	1281.04	2	640.52			
Model	1370.09	8	171.26	61.14	< 0.0001	*
A Time of Sieving	575.54	1	575.54	205.47	< 0.0001	*
B Rotation of the Starch	0.23	1	0.23	0.081	0.7773	
C Drying Timeo	0.31	1	0.31	0.11	0.7403	
AB	0.017	1	0.017	5.919E-003	0.93292	
A^2	494.31	1	494.31	176.47	< 0.0001	*
B^2	10.64	1	10.64	3.80	0.0604	
C^2	10.61	1	10.61	3.79	0.0607	
AB^2	90.02	1	90.02	32.14	< 0.0001	*
residual error	86.83	31	2.80			
lack-of-fit	18.34	6	3.06	1.12	0.3814	NS
pure error	68.49	25	2.74			
total col	2737.96	41				

Table 3. Summary of model *F*-value.

Std dev.	Mean	CV.%	R^2	Adj. R^2	Adeq. precision
1.67	26.87	6.23	0 9404	0.9250	30.422

Stad dev.: standard deviation. CV%: coefficient of variation. R^2: simple coefficient of determination. Adj. R^2: adjusted coefficient of determination. Adeq. precision: adequate precision.

A canonical analysis was performed to estimate the optimal working conditions of machine 2 and machine 3 to obtain the conditions of maximum operating performance.

From the model (Eq. 2), the response surfaces (Figure 4) were plotted for the factors studied and under the specified operating conditions. The non-local maxima (optimal starch yield) were achieved by the gradient ascending method (BOX & WILSON, 1951). Curvature inspection of the response surface, showed sufficient and necessary stability (no saddle points or local maxima), suggesting the existence of these optimum points unequivocally (Figure 5).

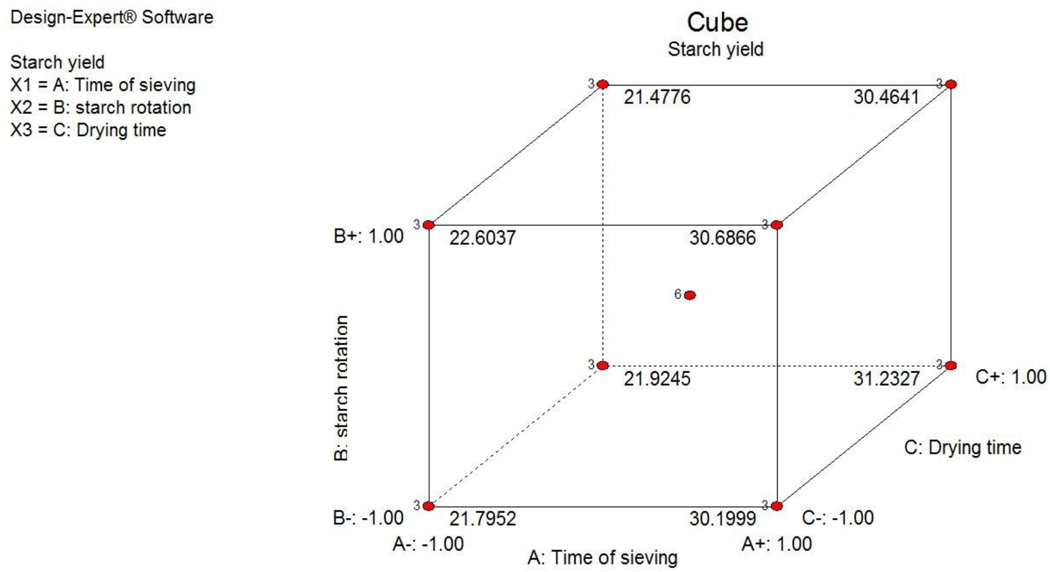

Figure 4. Cube regression reduced and hierarchized DCC model. The image shows the three evaluated factors, the code units, and the yield of starch obtained for each level. The Design-Expert v7.15 software (Stat-Easy, 2008) was used.

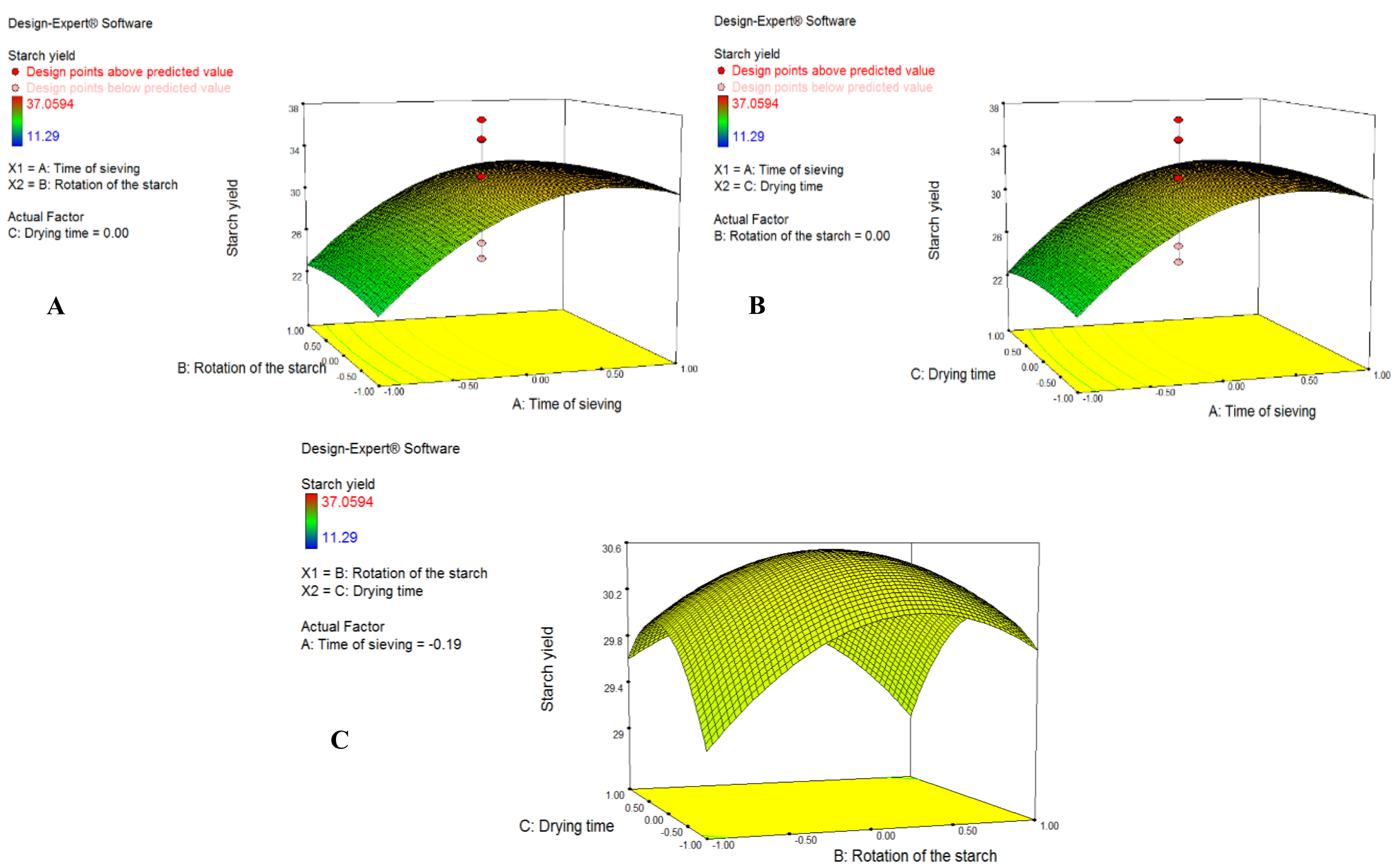

Figure 5. Response surface model (contours and 3-D views) of the starch yield for the designed technological process (MATILDA v1.0). Starch yield is displayed in percentage units, as explained in the previous sections, based on the predictor variables (A: rotation of the starch vs. time of sieving, B: drying time vs. time of sieving, and C: drying time vs. rotation of the starch). Predictor variables are shown dummy units. Also, prediction interval was shown. The software Design Expert v7.15 (STAT-EASY, 2008) was used.

The estimated optimal points were obtained: sieving time (45 min); starch removal time (3 turns during the drying period) and drying time (4 h 20 min) with a temperature range of 40-60°C for the maximum yield confidence interval of 30.24-32.97% and a prediction interval of 27.98-35.23%.

These designs can be modified and adapted to the conditions and needs according to the zone or country and their energy capacities to improve the yucca yields; thus, if there is an access to electricity and facilities to adapt mechanical force through an electrical system, this would reduce the times of starch extraction. It is necessary to emphasize the use of alternative energies such as hydraulic and wind, which are very easy to adapt, depending on the conditions of the area to be used. Regarding the solar furnace, the possibility of adapting forced ventilation is proposed, which would allow a faster and even starch drying. These machines could be made with more resistant materials such as stainless steel to make them more durable.

CONCLUSIONS

The three machine prototypes were designed and constructed for yucca root processing., it was possible to verify a substantial water saving and the high yield of the final product. This takes into consideration the security this system provides to the operator and the ease of its manipulation, simplifying the process of artisan extraction of the yucca starch.

The artisan extraction process (washing/peeling, grating/sieving/sedimentation) of the starch was optimized by the response surface methodology, obtaining a superior performance compared to the reported one to conventional artisanal processes. It is emphasized that during the drying process, which was carried out in the solar furnace, the desired humidity was not obtained due to the climatic conditions of the area. This system for starch extraction directly impacts the peasantry, since the developed system would allow obtaining extra economic benefits with the processing of yucca roots that often represent a marginal crop, thus, improving their quality of life.

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