PARAMETER OPTIMIZATION OF A PLASTIC REMOVAL MECHANISM FOR COTTON GINS

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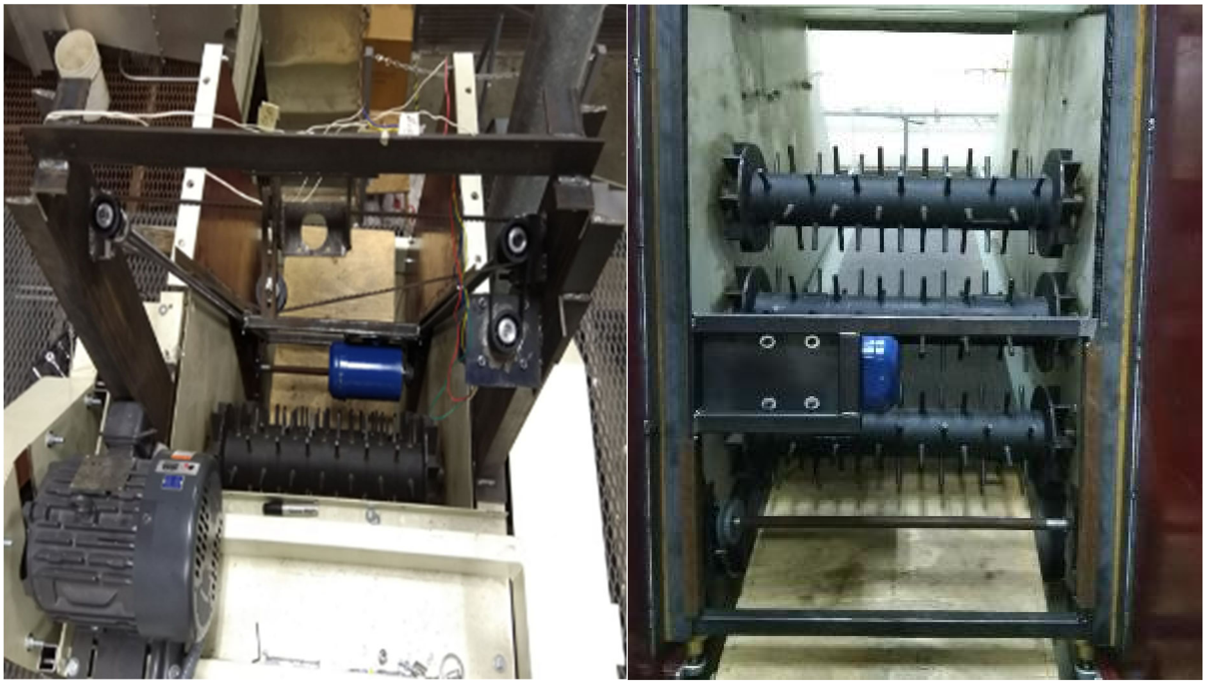
Abstract

To maintain its reputation as the producer of some of the cleanest cotton in the world, the U.S. cotton industry has committed significant effort towards preventing plastic contamination. Plastic covers from round modules are the predominant source of plastic contamination; roadside trash that collects at the edge of cotton fields, such as discarded shopping bags, may also result in plastic extraneous matter in the bale. In response to the plastic contamination challenge, we designed and fabricated a variable-speed brush-based plastic removal mechanism that can be scaled up for installation/retrofitting on many existing commercial seed cotton module feeders. Earlier preliminary tests and analyses had shown us that the most dominant parameters that affect the performance of this plastic contamination removal mechanism are the brush cylinder speed, the dispersing cylinder speed, and the duration of cleaning/removal operation, when the appropriate optimal brush gauge is used. This current work presents the results of the optimization of these operational parameters for the stainless-steel brush-based mechanism at our microgin laboratory, prior to its future deployment and testing on full-scale commercial gin module feeders. A circumscribed central composite (CCC) design was used for optimization of speeds and duration for different plastic sizes. The results of the optimization show that our brush-based mechanism is a viable option for removing plastic pieces from module feeder cylinders and confirmed interactions among some of the explanatory factors. There was a statistically significant interaction effect between the brush speed and cleaning time, so that with moderate brush speeds, the plastic may still be removed with a longer cleaning time. However, too low a brush speed will result in nearly zero plastic removal. Overall, the optimal range of the parameters are slightly outside the current design space and future work will be based on the newly identified levels for the four factors.

Introduction

The cotton industry is an important segment of the larger U.S. agriculture industry as it contributes, on a yearly basis, more than $21 billion in products and services and employs over a hundred thousand individuals from farm to textile mills (USDA-ERS, 2020). Cotton originating from the U.S. has traditionally enjoyed premium prices, due particularly to their contamination-free quality (ITMF, 2014). However, in recent years, following the introduction and high adoption rate by cotton producers of some commercial harvesters with automatic on-board module building capability, the U.S. cotton industry has been facing serious economic and reputational challenges from plastic contamination, particularly from the protective plastic covers used in wrapping the round modules that are made by these automatic module builders (Mitchell and Ward, 2020; Haney and Byler, 2017). Although the plastic covers serve a major function of protecting the seed cotton from weather, when they break down due to mechanical damage or entrapment on the cylinders of module feeders at commercial cotton gins, they become problematic for conventional gin cleaning equipment to remove (Adeleke et al., 2021). Other sources of plastic contamination found in cotton bales include films used for mulch and plastic bags that are picked up in fields adjacent to residential areas or roads by mechanical harvesters during harvesting.

Many research efforts have been committed to solving this problem, including those presented in Adeleke et al. (2021), Pelletier et al. (2020), Wanjura et al. (2020), and Wanjura et al. (2021). Earlier in our work (Adeleke et al., 2021), we proposed, designed, and fabricated a brush-based plastic removal mechanism (Figure 1) for the removal of plastic pieces that are trapped on the dispersing cylinders of module feeders. This location is where the contaminants first contact the ginning equipment and thus, a logical choice to target for removal. In this current work, we present the parameter optimization of the designed mechanism in Adeleke et al. (2021) for maximum plastic removal performance based on brush shaft speed (RPM), dispersing cylinder speed (RPM), the duration of the plastic removal operation (s), and the size of the plastic being removed (m or ft).



(a) (b)

Figure 1. The designed brush-based plastic removal mechanism: (a) top view, (b) front view.

RSM is a collection of mathematical and statistical techniques available for experimental model generation and investigation and has gained application in a range of disciplines for optimizing target responses. It is a potent tool for testing multi-process variables as it only requires a small number of experimental runs and resources compared to one-factor-at-a-time studies. The groundwork of the technique was presented in Box and Wilson (1951). A theoretical background of RSM and the selection of an appropriate CCD for a particular application may be found in Oyejola and Nwanya (2015). The CCD has gained popularity in the estimation of models that are suspected to have second-order response surfaces. CCD's contain embedded factorial or fractional factorial designs (with resolution V) with center points that are augmented with a group of star points which permit approximation of curvature. Therefore, the choice of our design for the optimization in this work is the circumscribed central composite (CCC) design, which is a variety of the CCD.

Objectives

The overall goal of this research was to determine the ranges of the four chosen explanatory parameters—brush speed (RPM), cylinder speed (RPM), cleaning time (s), and plastic size (ft or m)—where the plastic removal efficiency of the brush-based mechanism is maximized. Thus, the objectives of this work were to:

- Optimize the operating parameters of our designed mechanism for maximum plastic removal efficiency
- Identify statistically significant model(s) sufficient for explaining the effects of the individual parameters
- Minimize shredding of the plastic removed from the dispersing cylinders.

Materials and Methods

An estimate of the optimal ranges of the four explanatory factors in the CCC design was obtained from preliminary test runs and used as the basis for determining tested factor levels. For plastic size, the minimum plastic size that can be trapped on the cylinder was identified to be about a quarter of the full width of a module wrap, which is about 8 ft [2.4384 m], and thus, the lower- and upper-star point levels of plastic size factor were chosen as 1.5 ft [0.4572 m] and 8 ft [2.4384 m], respectively. Although we experimented with both plastic shopping bags and module wrap during preliminary testing, we only conducted the final optimization experiments using plastic module wrap. Plastic module wrap has been a much more common source of contamination.

Target Response Variable

The main objective of this work was to maximize the plastic removal performance of our mechanism with as minimal shredding of the plastic as possible. However, since this a novel mechanism, there is no known metric for evaluating this performance. We had to define a continuous, numerical metric that can be used to evaluate the performance of our mechanism in removing trapped plastic on the dispersing cylinders. We defined the *plastic removal efficiency (%)* as the fraction of the initially trapped plastic mass (g) that was removed by the brush action during the duration (factor C level) of a particular experimental run, expressed in percentage. However, since a system has not yet been designed to convey the removed plastic out of the module feeder, recovering all removed plastic is difficult. Therefore, the efficiency metric was computed numerically in a reverse order as given in equation (1):

$$\varepsilon(\%) = \left[1 - \left(\frac{M_f}{M_I}\right)\right] * 100 \tag{1}$$

where ε is the plastic removal efficiency expressed in %, M_f is the mass (g) of plastic left on the cylinder after a removal/cleaning operation duration, and M_I is the mass (g) of plastic initially trapped on the dispersing cylinder before a removal/cleaning operation.

Experimental Design Matrix

In line with the CCD method, we arranged the design matrix into 3 blocks consisting of 2 factorial blocks and 1 axial/star block to achieve orthogonality. The corresponding actual values to each of the coded factor levels are presented in Table 1. For instance, the lower axial point (-α) and the upper axial point (+α) levels for the brush speed factor were set at 300 and 1000 RPM, respectively.

Table 1. The actual values corresponding to each of the coded factor levels.

Factor	Factor levels				
	-α	-1	0	+1	+α
A-Brush speed (RPM)	300	475	650	825	1000
B-Dispersing cylinder speed (RPM)	10	117.5	225	332.5	440
C-Cleaning time (s)	15	22.5	30	37.5	45
D-Plastic size (ft)	1.5	3.125	4.75	6.375	8

Experimental Procedure

The procedure for each run was standardized to have a good level of repeatability and model actual ginning processes as closely as possible. Each experimental run started by including the appropriate plastic size of a known mass in a miniature compacted seed cotton module. The plastic-contaminated module was fed into the module feeder at the Texas A&M microgin, allowing the plastic to get trapped on the dispersing cylinder. After plastic pieces were caught on the cylinder, the dispersing cylinders were stopped, and the remaining module backed out of the feeder. The lead screw positioning system, which is actuated by a stepper motor controlled from a Raspberry Pi microprocessor unit, aligned the brush shaft axis with the cylinder on which the plastic was entangled (Adeleke et al., 2021).

Next, the dispersing cylinders were started and set to the desired speed level using the manufacturer-installed speed controller. Thereafter, the brush motor (a Hallmark Industries MA0515E 1.5 hp AC motor), which was controlled via an ACS150-01U-06A7-2 variable frequency drive (ABB, Helsinki, Finland) was run at the frequency corresponding to the desired brush speed and for the duration for the experimental run being performed. It was possible to run the VFD locally using the keypads on the physical module, or remotely using control signals from the Raspberry Pi unit together with our pre-set frequency stored in the VFD's macro.

After the cleaning duration indicated for that specific experimental run elapsed, the remaining plastic left on the dispersing cylinder, if any, was carefully retrieved and measured on a PC 400 weighing scale (Doran Scales Inc., Batavia, IL USA), which has 0.1g accuracy. Finally, the plastic removal efficiency was computed for the specific run using equation (1). These experimental steps are summarized in Figure 2. The collected data was analyzed using Design Expert 13 software.

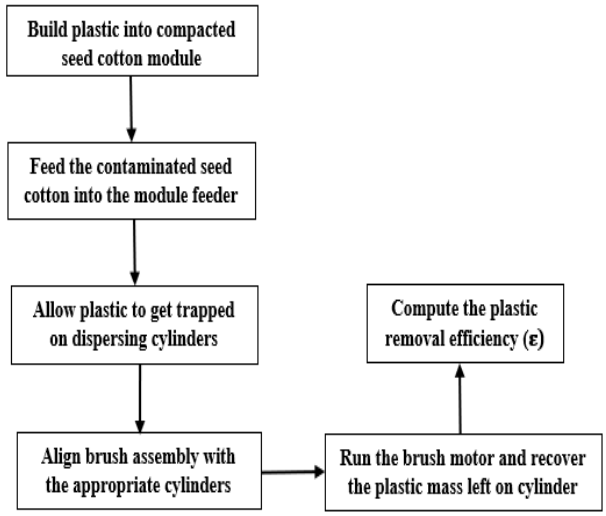


Figure 2. A summary of the procedures for each experimental run in the design matrix.

Results

Full-Order Quadratic Model

To select the most appropriate polynomial model, the sequential and lack of fit p-values were used to check which terms' addition to the linear terms had significant incremental effects. Only the addition of the quadratic terms had significant sequential p-value (0.0803) at the 10% significance level. Other terms were not significant; in fact, the cubic term is aliased (Table 2).

Table 2. The sequential and lack of fit p-values for different model terms.

Source	Sequential p-value	Lack of Fit p-value	Comment
Linear	0.4825	0.7777	
2FI	0.4264	0.7833	
Quadratic	**0.0803**	**0.9238**	**Suggested**
Cubic	0.8783	0.7054	**Aliased**

However, the overall full quadratic model was not significant (p-value = 0.160), and all the individual factors did not have significant effects as well. However, both the 2-factor interaction (2-FI) between the brush speed (A) and cleaning time (C) factors (A × C), and the squared brush speed (A^2) terms have significant effects (Table 3). Although the model is not significant enough to adequately explain all the variations in the process, the data is sufficiently rich enough to make the model good for exploring the design space as indicated by the adequacy of precision value of 4.5813, which is a measure of signal-to-noise ratio and deemed good if greater than four.

Although the model's R^2 value is fair (only 0.6534), the adjusted R^2 value of 0.2802 for the full quadratic model is quite low, confirming that the effects of the two significant terms in the full quadratic model is not sufficient to explain much of the variation in the data. Furthermore, the predicted R^2 greatly differs from the adjusted R^2 by more than 0.2, which may suggest overfitting. However, there is good evidence that no multicollinearity exists among the different terms (factors) of the model as indicated by all the variance inflation factor (VIF) values unity or close to unity (maximum VIF is 1.05). Equation 2 gives the full-order regression model in terms of the coded factor level coefficients.

$$\boldsymbol{\varepsilon_1}(\%) = 68 + 7.94A - 13.08B - 1.94C - 8.52D + 22.33A*C - 12.79A*D + 2.49B*C - 8.11BD - 2.85C*D - 21.27A^2 - 7.74B^2 + 3.60C^2 - 3.60D^2 \qquad (2)$$

Table 3. ANOVA table for the full-order model.

Source	df	Mean Square	F-value	p-value
Block	2	6179.28		
Model	14	2581.42	1.75	0.1604
A-Brush Speed	1	1511.95	1.03	0.3297
B-Cylinder Speed	1	4108.78	2.79	0.1190
C-Cleaning Time	1	90.40	0.0613	0.8083
D-Plastic Size	1	1743.84	1.18	0.2966
AB	1	1099.92	0.7459	0.4034
AC	1	7979.58	5.41	0.0368
AD	1	2617.14	1.77	0.2057
BC	1	99.08	0.0672	0.7995
BD	1	1051.27	0.7129	0.4137
CD	1	130.26	0.0883	0.7710
A^2	1	12414.50	8.42	0.0124
B^2	1	1641.51	1.11	0.3106
C^2	1	355.97	0.2414	0.6314
D^2	1	355.97	0.2414	0.6314
Lack of Fit	10	993.68	0.3229	0.9238

Generally, at low dispersing cylinder speeds and short cleaning times, the model predicts that as the brush speed increases from low to high level, plastic removal efficiency slightly and significantly decreases for medium and large plastic sizes, respectively, but conversely increases for small plastic size. Although, at longer cleaning times with low dispersing cylinder speeds, the model predicts that the cleaning efficiency significantly increases for all the plastic sizes. However, at high dispersing cylinder speeds and short cleaning times, the plastic cleaning efficiency declined with increasing brush speed and indicated no plastic removal for large plastic sizes. This result contrasts with the response predicted at high cylinder speed and long cleaning duration, where the cleaning efficiency is predicted to generally increase for all plastic sizes as brush speed increases, but the efficiencies at low brush speed for all the plastic sizes are low with these conditions.

3D surface plots and 2D contour plots are presented in Figures 3 and 4, respectively, to illustrate some of the interaction effects of the explanatory factors on plastic removal efficiency of the mechanism within the design space.

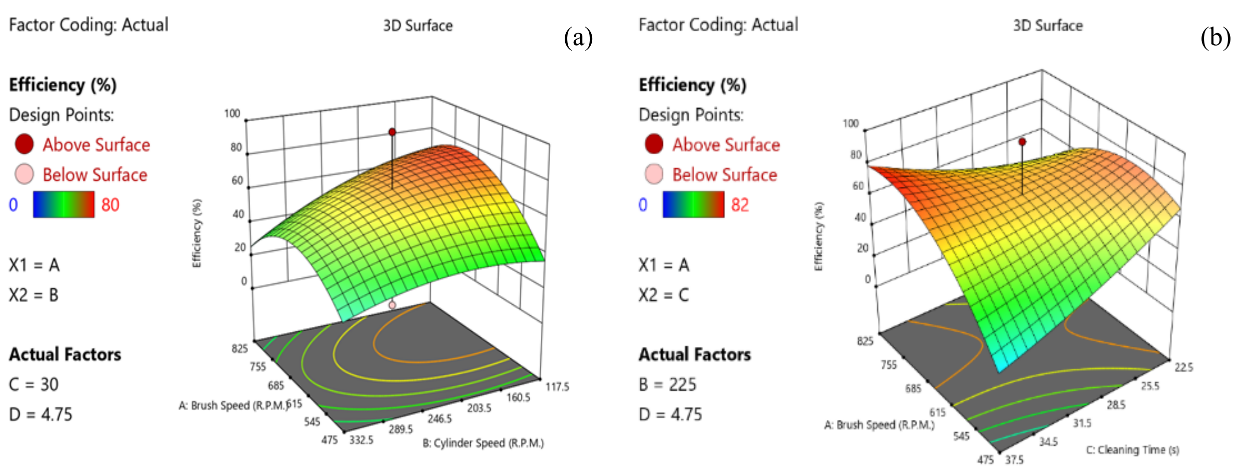


Figure 3. 3D response surface of $\boldsymbol{\varepsilon_1}$: (a) the interaction between the brush and the cylinder speeds, and (b) the interaction between the brush speed and cleaning time. Both are shown at the center levels of other factors.

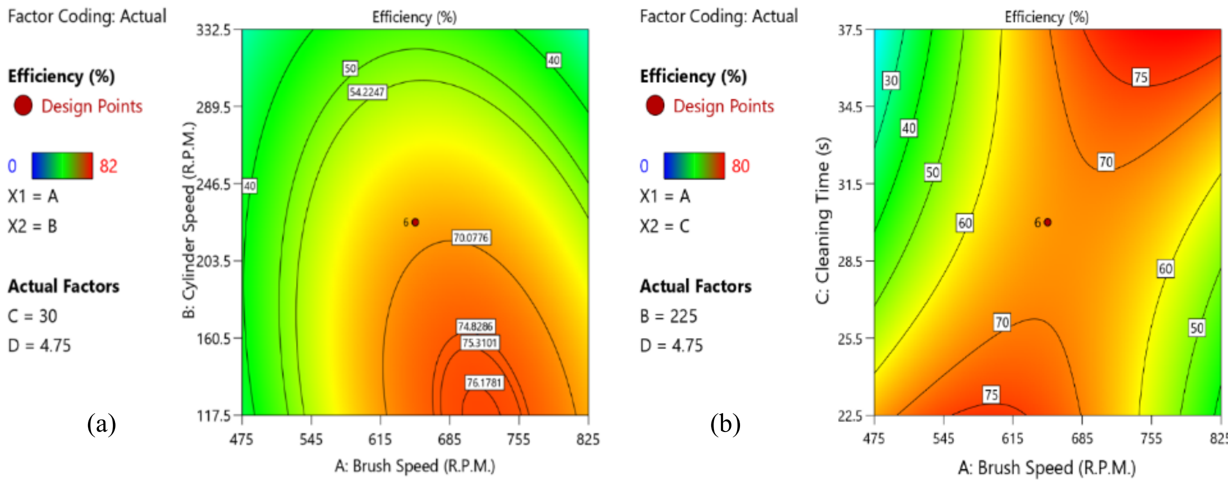


Figure 4. Contour plots of ε_1: (a) the interaction between the brush and the cylinder speeds, and (b) the interaction between the brush speed and the cleaning time. Both are shown at the center levels of other factors.

Reduced-Order Models

Because the full-order quadratic model was not significant, insignificant variables were eliminated, while maintaining model hierarchy, to generate significant models. Only two statistically significant (at 5% level) reduced-order quadratic models were identified. The first identified reduced-order model (Equation 3 and Table 4), has, in addition to the linear terms, all the brush speed interaction terms—A × B, A × C, and A × D—and its squared term, A^2. This model is not only statistically significant (with p-value = 0.0158 < 0.05), it also has at least two significant terms at the 0.05 significance level. The dispersing cylinder speed term has a p-value of 0.08 which may be accepted as significant at alpha = 0.1. Also, the gap between the R^2 value of 0.5806 and the adjusted R^2 value of 0.4 is quite small compared to the wider gap between these two values in the full-order model; this confirms the inclusion of higher proportion of terms that have a strong effect on the plastic removal efficiency in this reduced model, compared to the full-order quadratic model.

$$\varepsilon_2(\%) = 67.53 + 7.94A - 13.08B - 1.94C - 8.52D - 8.29A*B + 22.33A*C - 12.79A*D - 21.22A^2 \quad (3)$$

Furthermore, the F-value of 0.28 and the corresponding p-value of 0.96 for the model's lack of fit show that the generated model is sufficiently rich enough to explore the design space of the factors, much better than the full-order model which did not have statistical significance.

Table 4. ANOVA table for the reduced-order model 1.

Source	df	Mean Square	F-value	p-value
Block	2	6179.28		
Model	8	4014.33	3.29	0.0158
A-Brush Speed	1	1511.95	1.24	0.2796
B-Cylinder Speed	1	4108.78	3.37	0.0823
C-Cleaning Time	1	90.40	0.0741	0.7885
D-Plastic Size	1	1743.84	1.43	0.2467
AB	1	1099.92	0.9010	0.3544
AC	1	7979.58	6.54	0.0193
AD	1	2617.14	2.14	0.1595
A^2	1	12963.03	10.62	0.0041
Lack of Fit	16	872.63	0.2835	0.9608

This model predicts that when all the factors are maintained at their respective center values, it is possible to achieve about 67.5 % plastic removal efficiency, Equation 3. In addition, reducing the cylinder speed by 1 coded unit, while other factors are maintained at the center values has the potential to increase the achievable efficiency value by about

13%. Likewise, reducing plastic size by 1 coded unit while keeping other factors at their respective center values will likely increase the plastic removal efficiency by about 8.5%. However, the effect of changing the level of factor A is not as clear because of its interactions and squared term inclusion.

3D surface plots and 2D contour plots are presented in Figure 5 and 6, respectively, to illustrate some of the interaction effects of the explanatory factors on plastic removal efficiency of the mechanism within the design space.

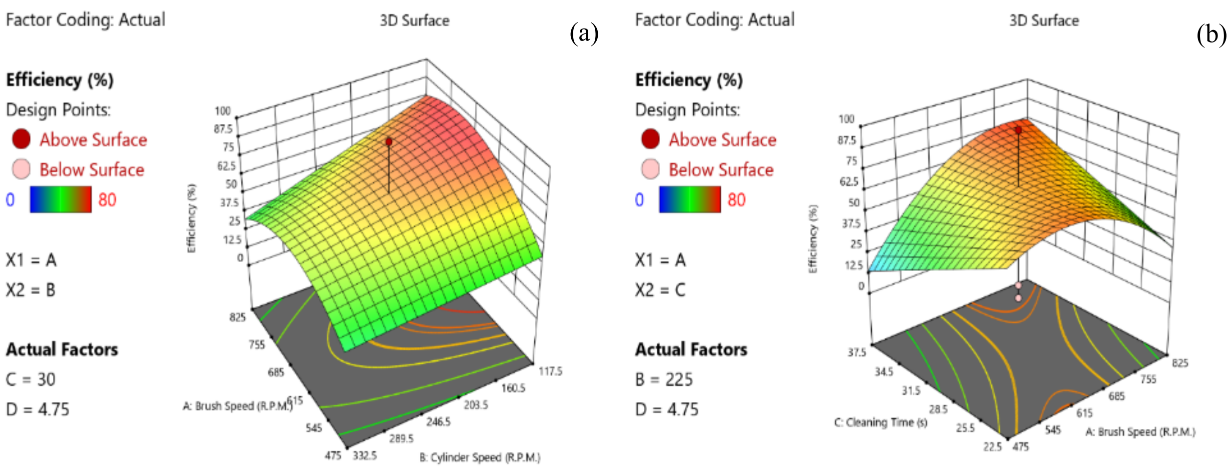


Figure 5. Response surface of $\boldsymbol{\varepsilon_2}$: (a) the interaction between the brush and the cylinder speeds, and (b) the interaction between the brush speed and the cleaning time. Both are shown at the center levels of other factors.

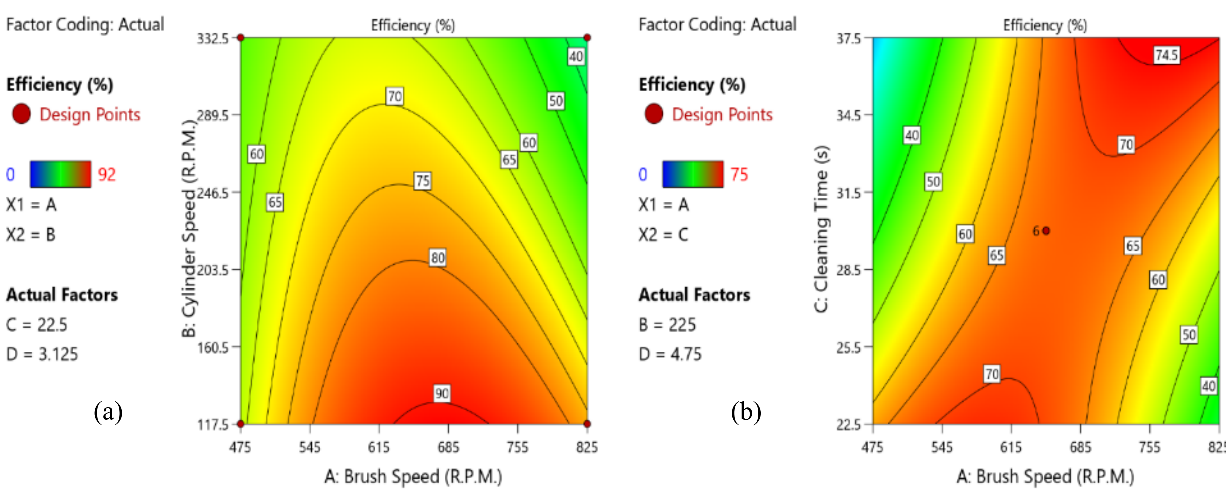


Figure 6. Contour plots of $\boldsymbol{\varepsilon_2}$: (a) the interaction between the brush and the cylinder speeds, and (b) the interaction between the brush speed and the cleaning time. Both are shown at the center levels of other factors.

The equation and ANOVA results for the second reduced-order model are presented in Equation 4 and Table 5, respectively. This model includes the linear terms of the factors, the brush speed and the cleaning duration interaction term, and the squared brush speed term. Like the first reduced-order model, it is statistically significant (p-value = 0.012), it also has the same significant terms as the previous reduced model. Similarly, the gap between the R^2 value of 0.5134 and the adjusted R^2 value of 0.3744 is smaller than for both the full-order and the first reduced-order model.

$$\boldsymbol{\varepsilon_3}(\%) = 67.53 + 7.94A - 13.08B - 1.94C - 8.52D + 22.33A * C - 21.22A^2 \qquad (4)$$

Table 5. ANOVA table for reduced-order model 2.

Source	df	Mean Square	F-value	p-value
Block	2	6179.28		
Model	6	4732.93	3.69	0.0116
A-Brush Speed	1	1511.95	1.18	0.2897
B-Cylinder Speed	1	4108.78	3.21	0.0878
C-Cleaning Time	1	90.40	0.0705	0.7931
D-Plastic Size	1	1743.84	1.36	0.2565
AC	1	7979.58	6.23	0.0210
A^2	1	12963.03	10.12	0.0045
Lack of Fit	18	982.18	0.3191	0.9488

The F-value of 0.3191 and the corresponding p-value of 0.95 for this model's lack of fit, similar to the first reduced model, show that this model is also sufficiently good enough to explore the design space of interest, much better than the full-order model, which was not statistically significant. In fact, the predictions of this model are not much different from that of Equation 3 since this model only dropped additional non-significant interaction terms.

The 3D response surface and the corresponding 2D contour plot for the brush speed and cleaning time factors are presented in Figures 7 and 8 as a visual aid in identifying the slight differences between the two reduced-order models.

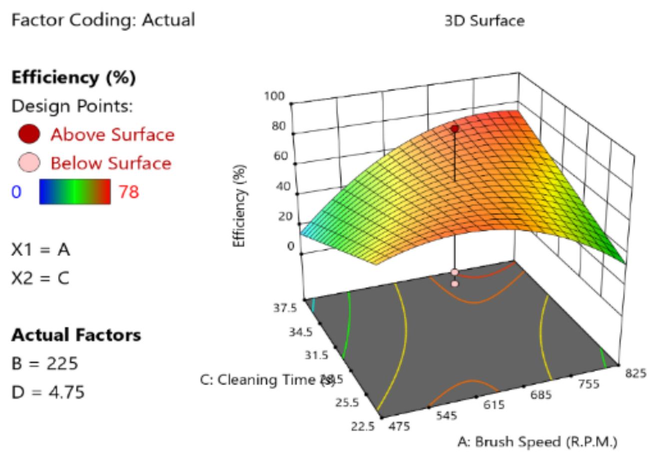


Figure 7. The response surface of ε_3 showing the interaction between the brush speed and cleaning time. Both B and D are kept at their center levels.

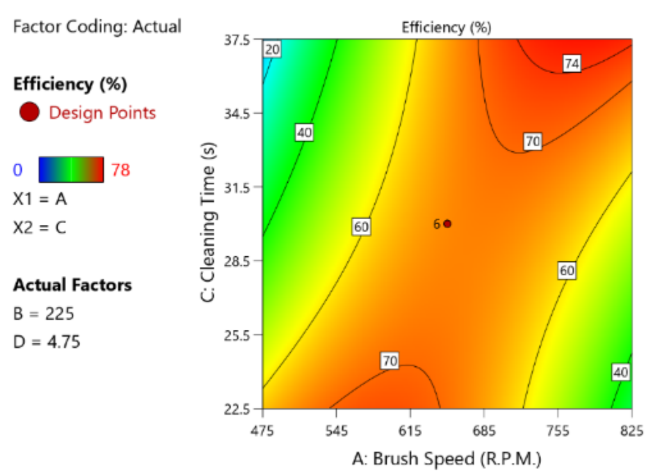


Figure 8. The contour plots of ε_3 for the interaction between the brush speed and cleaning time, with other factors at their center levels.

Future Work

Closer examination of the 2D contours and the 3D response surfaces generated in this work indicated that the optimal efficiency region is slightly outside the tested space of some factors. A design space closer to optimum has been identified and will be used for a refined future design to get the true optimal levels of the parameters that maximizes plastic removal efficiency of our mechanism (Table 6). Subsequently, a motorized modular plastic collection bin will be designed and incorporated with the optimized brush mechanism to enhance retrieval of the removed plastic pieces from the module feeder floor. Finally, the optimized mechanism integrated with an appropriate plastic sensing technique will be made ready for deployment and testing at some commercial gins.

Table 6. Future experimental factor testing levels.

Level	A: Brush Speed (rpm)	B: Cylinder Speed (rpm)	C: Cleaning Time (s)	D: Plastic Size (ft) [m]
-α	650	10	5	1.5 [0.4572]
-1	687.5	37.5	7.5	3.125 [0.9525]
0	725	65	10	4.75 [1.4478]
1	762.5	92.5	12.5	6.375 [1.9431]
α	800	120	15	8 [2.4384]

Summary

This work presents optimized a plastic removal mechanism that we designed, fabricated, and retrofit on the module feeder of a cotton gin. From preliminary testing four factors, brush speed, cylinder speed, cleaning duration, and plastic size, were identified that affect the plastic removal efficiency of the mechanism. Our objective was to maximize this plastic removal efficiency through an optimal combination of these factors, while minimizing shredding of the removed plastic. To minimize the resources needed for the optimization and generating a model that encompasses the interaction effects among the four factors, we opted for the use of circumscribed central composite design. This design also enabled us to generate polynomial models suitable for explaining the effects of the explanatory factors on the target response variable.

The results of the optimization show that our brush-based mechanism is a viable option for removing plastic pieces from module feeder cylinders and confirmed interactions among some of the explanatory factors. Based on our experimental data, the quadratic model is the best fit polynomial that represent the variation in the mechanism's efficiency as a function of the four selected factors. When the brush speed is high enough, plastic removal may occur rapidly, especially for small pieces of plastic. There was a statistically significant interaction effect between the brush speed and cleaning time, so that with moderate brush speeds, the plastic may still be removed with a longer cleaning time. However, too low a speed will result in nearly zero plastic removal. Finally, graphical plots suggested that the optimal region for maximum plastic removal efficiency is slightly outside the tested space of some of the explanatory factors and thus, additional testing is planned with factor levels closer to optimum.

Acknowledgements

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