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Modeling and Optimization of High-Capacity Experimental Reclaimers to Minimize the Seed and Lint Loss during Roller Ginning of Upland and Pima Cotton

Jaya Shankar Tumuluru *, Carlos B. Armijo, Derek P. Whitelock and Paul A. Funk

Southwestern Cotton Ginning Research Laboratory, United States Department of Agriculture, Agriculture Research Service (USDA-ARS), 300 E College Ave, Las Cruces, NM 88005, USA; carlos.armijo@usda.gov (C.B.A.); derek.whitelock@usda.gov (D.P.W.); paul.funk.phd@gmail.com (P.A.F.)

* Correspondence: jayashankar.tumuluru@usda.gov; Tel.: +1-575-526-6381

Abstract: In the present study, two high-capacity experimental roller gin reclaimers, (a) a modified 3-saw cylinder stick machine (three-saw) and (b) a modified 2-saw cylinder gin stand feeder (700), were optimized with respect to reclaimer saw cylinder speed and carryover/seed ratio to minimize the seed and lint loss for both Pima and Upland cotton varieties and were compared to a conventional roller gin reclaimer operated by the ginning industry under standard conditions. Developed regression models adequately described the seed and lint loss phenomena during the reclaiming process. Surface plots indicated that the reclaimer saw cylinder speed and carryover/seed ratio impacted the seed and lint loss for both the 3-saw and 700 reclaimers. Under optimized conditions, the 700 reclaimer resulted in lower lint and seed loss compared to the 3-saw reclaimer when using Upland cotton. In the case of Pima cotton, under optimized conditions, the 3-saw reclaimer had 38% lower lint loss and 24% higher seed loss compared to the 700 reclaimer. The regression equations of both 3-saw and 700 reclaimers were further used to optimize the reclaimers in parallel arrangement to minimize the seed and lint loss. With Upland cotton, the economic loss was about 2.5 times greater with the conventional reclaimer compared to the 3-saw and 700 reclaimers ($15.97/bale loss for the conventional, $8.63 for the 3-saw, and $6.44 for the 700 reclaimers). With Pima cotton, the conventional reclaimer resulted in a lower economic loss ($3.44/bale) compared to the 700 reclaimer which had a loss of about $3.59/bale.

Keywords: cotton variety; roller ginning; roller gin reclaimer; lint loss; seed loss; non-linear regression models; surface plots; optimization; hybrid genetic algorithm

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1. Introduction

Currently, the top cotton producing countries include China, India, the United States and Brazil. China's 2022/2023 crop—the world's largest—is estimated at 28.5 million bales, up 1.7 million bales from the previous year [1]. The U.S. cotton production in 2023/2024 is expected to rise to 15.8 million bales [1]. In the United Sates, Upland and Pima (extra-long staple) are the two main cotton species cultivated for commercial use and for export. The primary difference between the two species is fiber length, and end use applications [2]. Ginned U.S. cotton is graded by the USDA Agricultural Marketing Service classing offices, using the High-Volume Instrument (HVI). HVI provides fiber quality parameters such as upper half mean length, uniformity index, strength, micronaire, trash count, reflectance (Rd), yellowness (+b); these properties have a great impact on the finished textile products. Some of the important HVI properties of Upland and Pima grown in the U.S. Southwest (Texas, Oklahoma, Kansas) and the far West of the USA (California, Arizona, New Mexico) are given in Table 1 [3].

Table 1. Upland v. Pima Cotton Characteristics after ginning.

Cotton Types	Percentage of U.S. Production	HVI Properties	End Uses
Upland (*Gossypium hirsutum*)	97%	UI (%): 80.3 UHML (mm): 28.194–28.702 Micronaire: 3.94 Strength: 30.5	Apparel, home use (curtains, upholstery, etc.), hospital/medical use
Pima (*Gossypium barbadense*)	3%	UI (%): 81.2 UHML (mm): 29.972–30.48 Micronaire: 4.29 Strength (g/tex): 32.2	Expensive/high end apparel, sewing thread

Figure 1 gives the unit operations to process seed cotton modules or bales in a commercial gin in the US. Among these unit operations, ginning accomplishes the main operation of separating the lint from the seed. There are three types of gin stands (saw-type, rotary-knife roller or roller and reciprocating) which are used for cotton ginning and in the U.S. only the roller and saw type gin stands are used. The gin type used depends on the cotton that is processed. To preserve fiber quality, only roller gins are used to gin extra-long staple *Gossypium barbadense* cottons such as Pima, whereas all gin types can be used to gin *G. hirsutum* cottons such as Upland. Although roller ginning is slower than saw ginning and used on a smaller scale to gin about 4% of the U.S. crop [4], it is sometimes also used to gin select Upland cottons, e.g., Acala, to protect its fiber value, as spinning mill customers are willing to pay slightly more for the superior quality fiber [5].

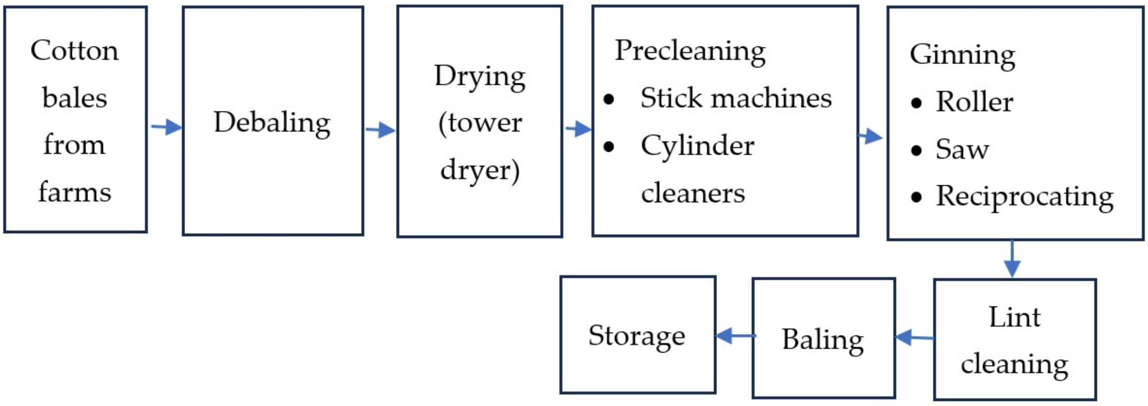

Figure 1. Unit operations used for processing of seed cotton received from farms.

Roller gins were the first mechanical systems to separate lint from seed [6]. Figure 2 is a diagram of the rotary-knife roller gin [7]. The major components of the roller gin are the (1) roller, (2) rotary knife, and (3) stationary knife (Figure 1). The rotary knife helps to direct the seed cotton to the ginning point—the point where the stationary knife contacts the roller. Lint adheres to the roller covering and is drawn under the stationary knife, removing it from the seed. The rotary knife also removes the ginned seed and unginned seed cotton (called carryover) from the ginning point. If a roller gin stand is properly fed, it will typically have three to five percent carryover [8]. The ginned seed and carryover fall onto a belt and are conveyed to a reclaimer for separation.

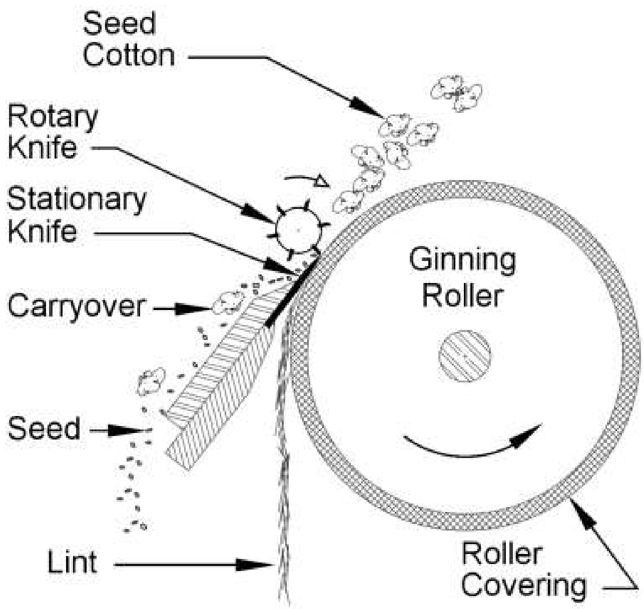

Figure 2. Principle of the rotary-knife roller gin [7].

1.1. Background to Reclaimers

Reclaimers are specialized machines that separate the carryover from the ginned seed and send it back to the gin stand for re-ginning. In reality, the carryover sent back for re-ginning contains some ginned seed (residual seed), and the ginned seed contains some carryover (residual carryover). An ideal reclaimer will recover all the carryover without any residual seed and all the seed without any residual carryover. Figure 3 shows material flows for a typical reclaimer [7]. A typical roller ginnery has 16 rotary knife gin stands [9]; a single reclaimer usually handles carryover from six to eight gin stands. Conventional reclaimers typically contain saw cylinders, grid bars, and doffing brushes. During reclaiming, carryover is picked up off the seed belt by circular saws partially surrounded by grid bars. The grid bars help to separate any seed that was picked up with the carryover. The separated seed falls back onto the belt and is conveyed to seed storage. The doffing brush removes the carryover from the saws and returns it to the gin stand for processing.

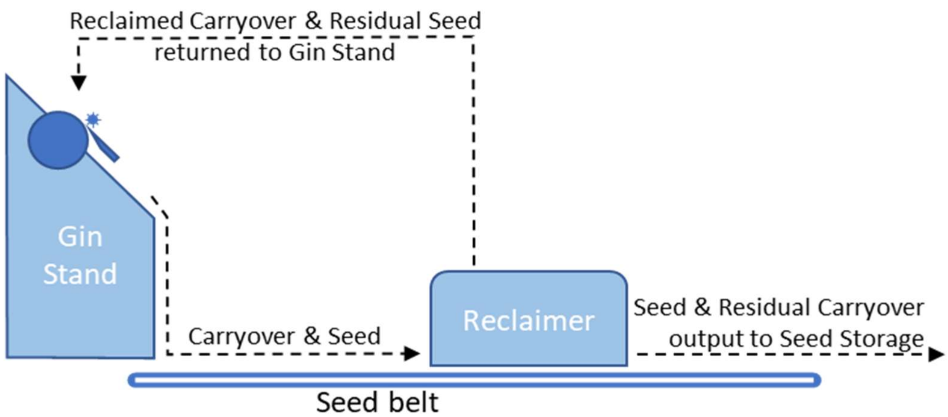

Figure 3. Material flow in a reclaimer [7].

Armijo et al. [7] recently evaluated a modified 3-saw cylinder stick machine (3-saw) and a modified 2-saw cylinder gin-stand Model 700 feeder (700) as alternative experimental high-capacity seed-cotton reclaimers for high-speed roller ginning. The study indicated that the 3-saw and 700 reclaimers reclaimed more carryover than the conventional reclaimer. On the other hand, the conventional reclaimer had less residual seed loss than the 3-saw and 700 reclaimers, but resulted in more residual carryover (lint loss). The results of this study also indicated that increasing saw-cylinder speed on the experimental reclaimers decreased seed loss but increased lint loss.

High-speed roller ginning has become a commercial standard [5]. There are advantages of roller ginning Upland cotton as it results in longer and more uniform fiber, and less short fiber and neps than saw ginning. However, conventional reclaimers were designed for conventional roller-ginning production rates and, therefore, sometimes struggle to handle the additional carryover amounts of the high-speed roller-ginning process; this may lead to choke-ups and downtime for the ginnery. Additionally, conventional reclaimers allow more fiber to escape with the seed when roller ginning Upland cotton. Therefore, there is a need to test alternative and potentially higher-capacity reclaimers to meet the higher throughput demanded by high-speed roller ginning and optimize the process to minimize the seed and lint loss to minimize the economic loss to the stakeholders.

In general, response surface methodology (RSM), which is a combination of mathematical and statistical techniques, is commonly used for process modelling and optimization [10–13]. RSM usually represents data as a polynomial with coefficients determined through least-squares regression. Surface plots drawn based on RSM models help to understand the interaction effect of process variables and product properties [14–20]. In recent years, genetic algorithms (GA) have gained importance in optimization due to their ability to find optimized conditions for multi-dimensional complex problems while utilizing minimal resources [21–26]. Tumuluru and McCulloch [27] and Beg and Islam [28] determined that one of the major limitations of GA is that it is a heuristic method, it cannot reach the global optimum and converges prematurely, and also requires longer optimization times. To overcome this limitation, hybrid genetic algorithms are developed to search space more precisely and reach a global optimum.

1.2. Objectives

As mentioned earlier, Armijo et al. [7] collected residual carryover (lint loss) and residual seed loss data for conventional and experimental high-capacity reclaimers (a) a modified 3-saw cylinder stick machine (hereafter referred to as 3-Saw), and (b) a modified 2-saw cylinder gin stand feeder (hereafter referred to as 700) at different saw-cylinder speeds (hereafter referred to as reclaimer speed) ranging from 1/2 of full speed, 3/4 of full speed and full speed. However, these authors did not model or optimize the reclaiming process in terms of carryover/seed ratio and reclaimer speed, or with respect to response variables such as lint and seed loss per bale. Furthermore, no literature regarding process models and optimization for experimental high-capacity reclaimers using Pima and Upland cotton is available. Based on this, the overall objective of the present study was to model and optimize the 3-Saw and 700 experimental high-capacity reclaimers using data generated by Armijo et al. [7]. The specific objectives of the research were:

- Develop response surface models and plots for the two experimental high-capacity reclaimers for process variables such as carryover/seed ratio and saw speed (full speed, $\frac{1}{2}$ of full speed, and $\frac{3}{4}$ of full speed for seed and lint loss during the process).
- Optimize the process using a hybrid genetic algorithm (HGA) for the two high-capacity reclaimers independently and when placed in a parallel arrangement.
- Compare the lint and seed loss for the two experimental high-capacity reclaimers under optimized conditions with the conventional reclaimer and evaluate the economic loss.

2. Materials and Methods

2.1. Research Data

Data from an experiment conducted by Armijo et al. [7] was used in the present data analysis, which includes modeling and optimization. The cotton used in the experiment included an Upland cotton (Dyna-Gro 3385) and a Pima cotton (Deltapine 340). In the experiment, the authors tested a conventional reclaimer which is typically used by the industry, and two experimental high-capacity reclaimers: (a) a modified 3-saw cylinder stick machine (referred to as 3-Saw in the paper), and (b) a modified 2-saw cylinder Lummus Model 700 III gin stand feeder (referred to as 700 in the paper). Figures 4–6 show the industry standard conventional reclaimer and the two high-capacity reclaimers tested in this project. Armijo et al. [7] discussed the operational features of these reclaimers in detail in their work to compare the experimental high-capacity reclaimers with the conventional reclaimer used by the industry for high-speed roller ginning and to understand the seed and lint loss. The saw-cylinders of the 3-saw and 700 experimental high-capacity reclaimers were run at three different reclaimer speeds (1/2 of full speed, 3/4 of full speed, and full speed) as controlled by variable frequency drive settings (30, 45, and 60 Hz, respectively). The saws of the conventional reclaimer were only operated at industry standard speed and referred to as 60 Hz for the purpose of comparison with the two high capacity reclaimers tested. Table 2 shows the reclaimer speeds of the 3-Saw, 700 and conventional reclaimers modeled in this study [7].

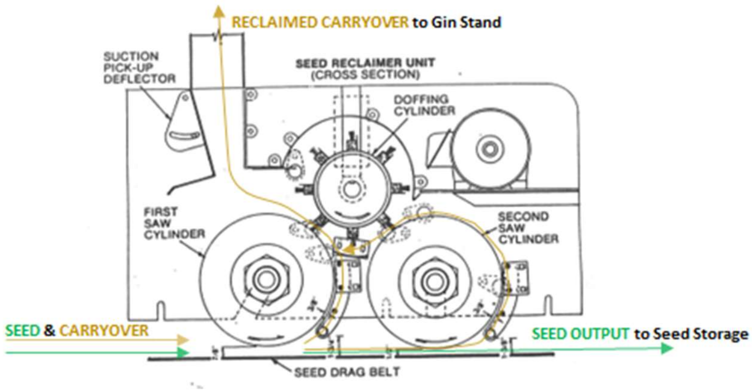

Figure 4. Conventional reclaimer used by the industry. Typical seed path in green and typical carryover path in gold (courtesy of Lummus Corporation).

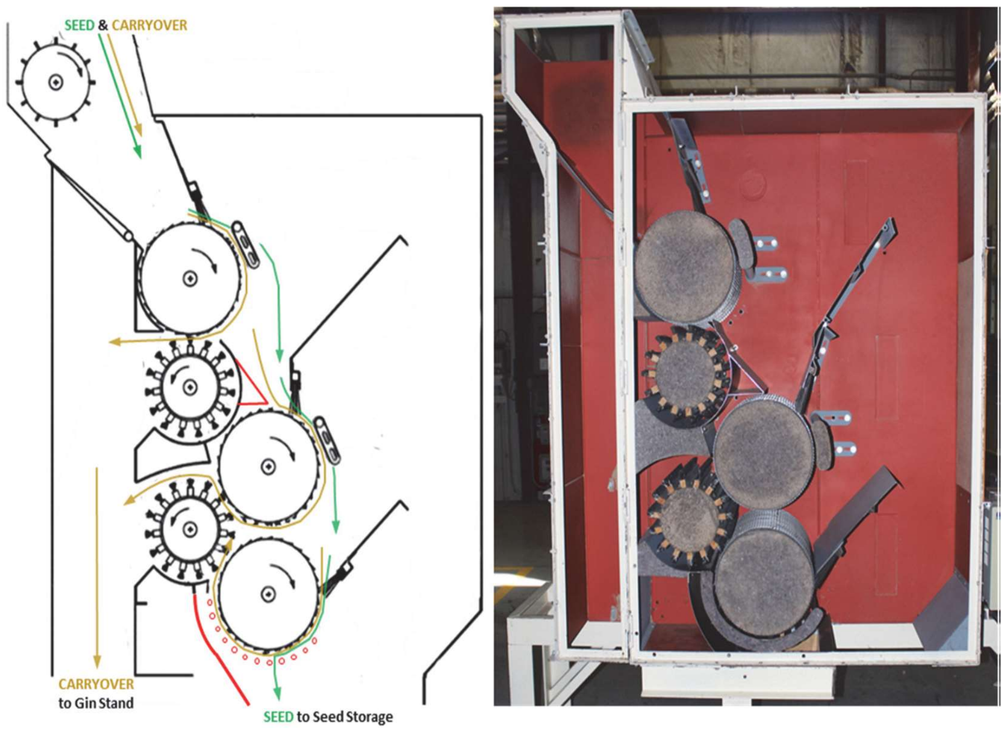

Figure 5. Modified 3-saw cylinder stick machine (3-saw) modeled in the present study. Added structures are indicated in red. Typical seed path in green and typical carryover path in gold [7].

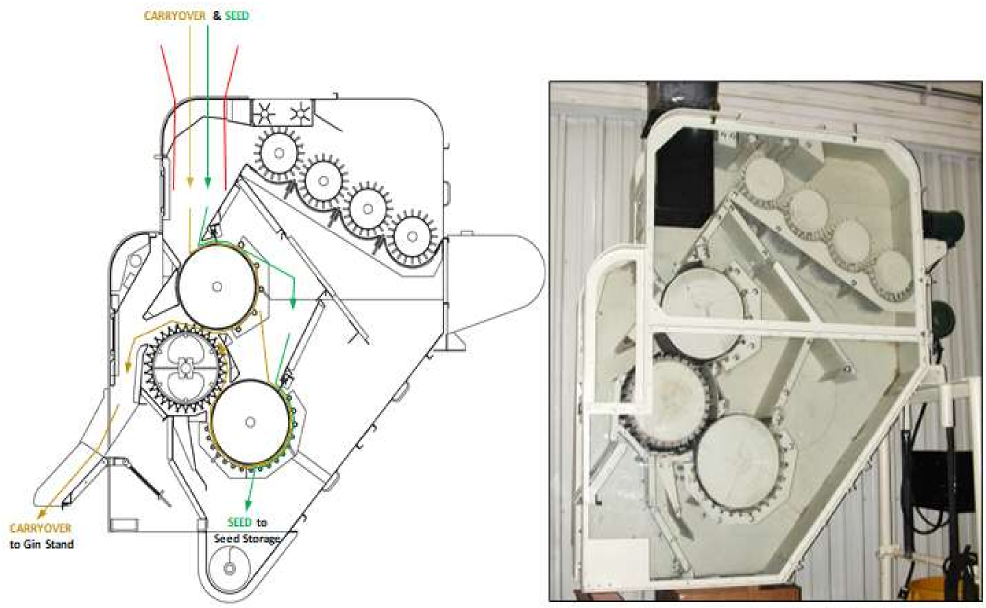

Figure 6. Modified Lummus Model 700 III feeder (700) modeled in the present study. Added structures are indicated in red. Typical seed path is shown in green and typical carryover path in gold [7].

Table 2. Reclaimer saw-cylinder speeds of conventional and high-capacity reclaimers.

Treatment	First or Top Saw Speed (rpm)	Second or Middle Saw Speed (rpm)	Bottom Saw Speed (rpm)
Conventional (Full) (60 Hz)	205	205	-na-
3-Saw-1/2 (30 Hz)	196	149	92
3-Saw-3/4 (45 Hz)	296	224	139
3-Saw-Full (60 Hz)	395	299	186
700-1/2 (30 Hz)	231	-na-	231
700-3/4 (45 Hz)	347	-na-	347
700-Full (30 Hz)	464	-na-	464

Note: VFD connected to the reclaimer's motor was used to control the reclaimer saw cylinder speeds. At 30 Hz the reclaimer saw cylinder speed ran at $\frac{1}{2}$ of full speed, at 45 Hz the saw cylinder speed ran at 3/4 of full speed and at 60 Hz the saw cylinder ran at full speed, na: not applicable. The reclaimer saw-cylinder speed is referred to as the reclaimer speed in the paper.

For each lot, 45.4 kg (100 lb) of seed cotton was precleaned and ginned on a 1.0-m (40-in.) wide Lummus high speed roller-gin stand. Pre-cleaning included two 6-cylinder incline cleaners and one stick machine, and since seed-cotton moisture content was 5–6% (w.b.) there was no drying of the seed cotton [7]. All the carryover and seed removed by the rotary knife from the gin stand was collected in a container and used for the reclaimer tests. The data generated for total carryover and seed removed were further analyzed for the carryover/seed ratio and used as an input variable for the reclaimer modeling. Figure 7 shows the flow diagram of the process tested. Table 3 presents the percent carryover/seed ratios and the reclaimer speed settings tested for the roller ginned Upland and Pima cottons using the conventional and experimental high-capacity reclaimers (3-Saw and 700). Each roller ginning test resulted in different carryover/seed ratios even though the roller gin was fed at a constant rate. The data on lint and seed loss collected by Armijo et al. [7] were converted to kilograms of seed and lint loss per bale using equations 1 and 2. Nine experiments were conducted for each experimental high-capacity reclaimer tested. The nine experimental data points were further used for modeling of the reclaiming process. The conventional reclaimer tests were performed in triplicate at 60 Hz (full speed), and the average of the three tests was reported.

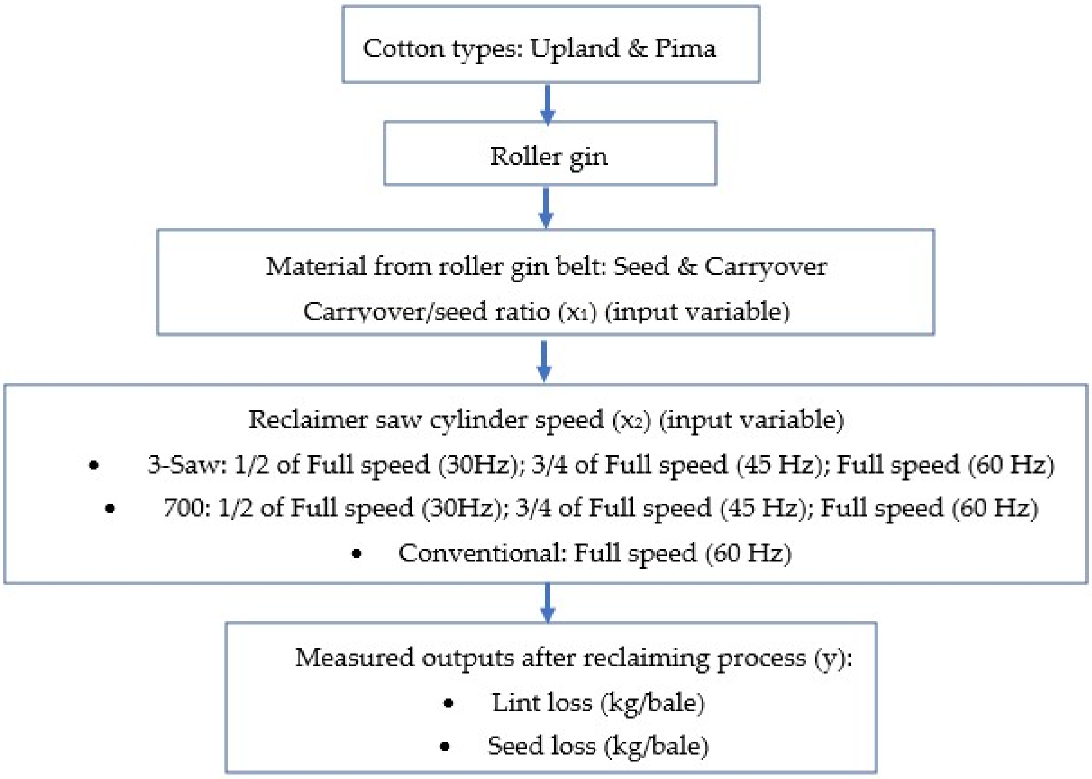

Figure 7. Process flow diagram for testing the high-capacity reclaimers.

Table 3. Reclaimer speed and carryover/seed ratios tested.

Modified 3-Saw Cylinder Stick Machine (3-Saw)		**Modified 2-Saw Cylinder Gin-Stand Feeder (700)**		**Conventional Reclaimer**	
CO/seed [a] (%) (x_1)	Reclaimer speed [b] (Hz) (x_2)	CO/seed (%) (x_1) [a]	Reclaimer speed (Hz) (x_2) [b]	CO/seed (%) (x_1) [a]	Reclaimer speed [b] (Hz) (x_2)
			Upland		
30.99–37.59	30–60	30.85–36.87	30–60	35.7	60
			Pima		
4.218–6.071	30–60	4.211–4.973	30–60	4.70	60

Note 1: [a] CO/seed = carryover/seed ratio in material removed by rotary knife. [b] The reclaimer saw-cylinder speed. The variable frequency drive connected to the motor of the reclaimer is used to control the speeds of the saw cylinders of the reclaimers. The details of the speeds of the reclaimers saw cylinder speeds are given in Table 1. Note 2: x_1 and x_2 are process variables used for modeling of the high-capacity reclaimer (3-saw and 700) tested in this project.

$$\text{Seed loss (kg/bale): A} \times \text{C} \tag{1}$$

$$\text{Lint loss: (kg/bale): B} \times \text{C} \tag{2}$$

where:

A: Residual seed in the carryover reclaimed (kg);
B: Lint on the residual carryover in the seed collected (kg);
C: Ratio of seed cotton per bale (589.7 kg)/seed cotton used per lot (45.4 kg) = 13.

2.2. Response Surface Models

Response surface models (RSM) were developed for lint and seed loss per standard bale with the process conditions percent carryover/seed ratio (x_1) and reclaimer speed (Hz) (x_2). The general form of the response surface model used is given in Equation (3) [18].

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \quad (3)$$

It is unlikely that a polynomial model will be a reasonable approximation of the true functional relationship over the entire space of the independent variables, but for a relatively small region, they usually work quite well. These models can be used as objective functions to find the optimum operating conditions for a system to determine the region where the requirements are most satisfied [10]. The RSM models were developed using Statistica software, version 14.1.0.8 [29]. ANOVA analysis of the experimental data was conducted to evaluate statistical significance effects of the process variables (carryover/seed ratio and reclaimer speed) on the response variables (seed and lint loss).

2.3. Optimization Scenarios Tested

The objective of the optimization studies was to identify the process conditions that can help minimize the seed and lint loss during the reclaiming process. The response surface models developed for carryover/seed ratio (x_1) and reclaimer speed (x_2) for the two types of reclaimers (3-saw and 700) for seed and lint loss were used for the optimization of the process for the minimum of lint and seed loss. The models developed for the two experimental high-capacity reclaimers were optimized in three different configurations:

(a) 3-Saw reclaimer for minimization of seed and lint loss
(b) 700 reclaimer for minimization of seed and lint loss
(c) Both 3-saw and 700 recalimers in a parallel arrangement to minimize the seed and lint loss (Figure 8).

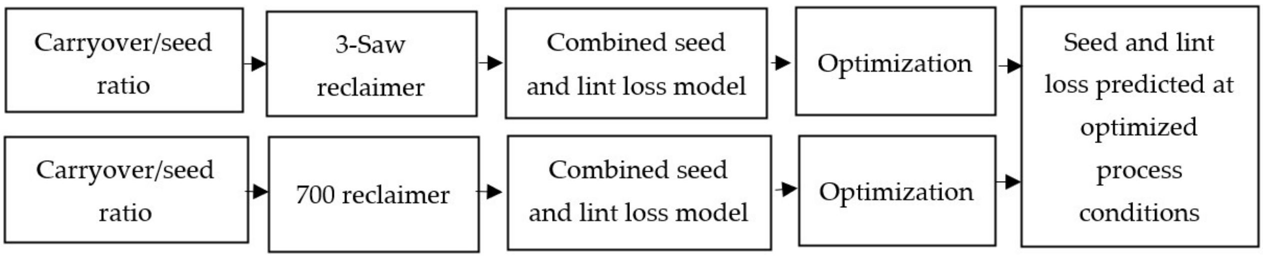

Figure 8. The 3-saw and 700 reclaimers in a parallel alignment.

A parallel arrangement is considered in the present research as it is practically implementable based on the data generated in this project. Additionally, the parallel arrangement can give better control of the carryover/seed ratio. Figure 8 show the arrangement of reclaimers in a parallel arrangement. In the present study the series arrangement of the high-capacity reclaimers was not considered as the carryover/seed ratio will change once it passes from one reclaimer to the next and we do not have the data to support this scenario. For individual optimization of each reclaimer, the individual seed and lint loss response surface models were used to identify the process conditions that can result in the lowest seed and lint loss. For the parallel arrangement optimization of reclaimers, the individual lint and seed loss models developed for the 3-saw and 700 reclaimers were used to develop the integrated model and were further optimized. In the parallel arrangement, the combined equation of seed and lint loss for the 3-saw and 700 reclaimers were optimized collectively to identify the process conditions that can result in the total minimum loss of lint and seed if placed in a parallel arrangement. Equation (4) shows the combined seed and lint loss equations used to optimize the reclaimers in the parallel arrangement.

$$\text{3-saw}: \text{ Total loss model}: \ f(total\ loss) = f(seed\ loss) + f(lint\ loss\ model) \quad (4)$$

$$\text{700}: \text{ Total loss model}: \ f(total\ loss) = f(seed\ loss) + f(lint\ loss\ model) \quad (5)$$

2.4. Process Model Optimization Methodology

Hybrid genetic algorithms are gaining importance as they optimize complex problems more precisely, compared to regular genetic algorithms. Maghawry et al. [30] developed a hybrid algorithm routine using a genetic and particle swarm algorithm. In this paper, the authors introduce a hybrid approach to optimize the evolving transformation sequences that utilize a genetic algorithm, to perform a global search which is supported by a particle swarm algorithm to perform a local search, so a balance between search space exploration and search space exploitation is thus achieved. These authors succeeded in optimizing the search process for the optimal program transformation sequence that targets a specific optimization goal. The results indicated that a hybrid approach applied to synthetic program transformation problems shows a significant improvement on the optimized output on which the hybrid approach achieved a Lines of Code (LoC) decline rate of 50.51% over the application of the basic genetic algorithm, where only 17.34% LoC decline rate was reached.

Tumuluru and McCulloch [27] found that integrating a deterministic algorithm subroutine into a genetic algorithm (hybrid genetic algorithm) helped to find the global optimum more precisely, and that the algorithm searches the solution space more thoroughly. The flowchart for the HGA algorithm is shown in Figure 9. These authors developed an HGA optimization tool on the MATLAB platform with a graphical user interface and have tested the optimization tool on benchmark Ackley and other food and bioprocessing functions. The HGA tool developed has the following features: the user can input the population size, number of iterations, elitism, crossover, mutation, lower and upper constraints, and tolerance. Furthermore, an optimal solution can be found within user defined boundaries. Additionally, the user can draw a surface plot for one objective function or for integrated multiple objective functions. These authors found that the HGA optimizes the biomass process more precisely than regular GA and tested HGA for various biomass processing methods, such as grinders and pelletizers [31,32]. The HGA developed by Tumuluru and McCulloch [27] was further used for optimization of the reclaimers individually and in a parallel arrangement.

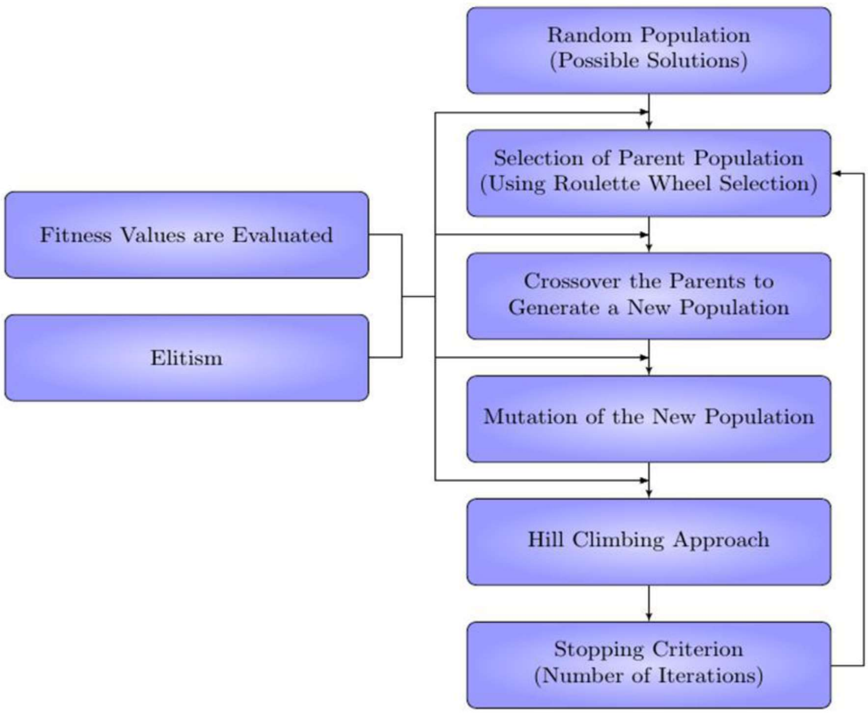

Figure 9. Hybrid genetic algorithm for optimization [27].

2.5. Economic Analysis

The economic analysis due to seed and lint loss for the two high-capacity reclaimers and conventional reclaimer were evaluated. For the two high-capacity reclaimers, the hybrid genetic algorithm optimized process conditions for minimization of lint loss and seed loss individually and in a parallel arrangement are used. In the case of the conventional reclaimer, the seed and lint loss when run at industry standard speed was used to calculate the economic loss. Table 4 indicates the optimization scenarios used for the economic analysis for the two experimental high-capacity reclaimers. In the present study both seed and lint loss were used as both have significant impact on the economic loss. The price for lint and seed is adapted from Armijo et al. [7] publication (Upland Lint price: $1.542/kg; Pima lint price: $3.172/kg; Upland seed cost: $300/ton ($0.30/kg) and Pima seed cost: $290/ton ($0.29/kg)).

Table 4. Optimization scenarios for economic loss estimation.

Cotton Types	Optimization Scenarios
Pima Upland	• 3-Saw: minimum of (a) lint loss and (b) seed loss process conditions • 700: minimum of (a) lint loss and (b) seed loss process conditions • 3-Saw and 700 in parallel arrangement: minimum of seed and lint loss process conditions

3. Results

3.1. RSM Models and Surface Plots

The data generated by Armijo et al. [7] was used to develop the second-order polynomial to describe the seed and lint loss for varying reclaimer saw-cylinder speeds and carryover/seed ratios. Table 5 indicates the regression models developed for the 3-saw and 700 reclaimers for the Upland and Pima cotton types. The models adequately described the process based on the coefficient of determination values and predicted and observed plots. Figures 10 and 11 show an example of the predicted and observed plots for lint and seed loss for the 700 reclaimers for Pima cotton. It is very clear from the plot that the predicted values were very close to the observed values, which indicates that the model prediction within the experimental limits studied was excellent. Additionally, the models developed were statistically significant, except the lint loss model developed for the 3-saw reclaimer for the Pima cotton.

The ANOVA analysis indicated that the linear terms of carryover/seed ratio and the quadratic term of carryover/seed ratio were significant for lint loss for the 3-saw reclaimer with Upland cotton. In contrast, for seed loss, the quadratic term of reclaimer speed was found to be statistically significant (Table 6). In the case of Upland lint loss with the 700 reclaimer, none of the process terms were significant, whereas, for seed loss, only the quadratic term of the reclaimer speed was statistically significant. In the case of the 3-saw reclaimer with Pima cotton, the linear and quadratic terms of the reclaimer speed were statistically significant, whereas, for the seed loss, none of the terms were statistically significant. In the case of the 700 reclaimer, both process conditions' linear, quadratic and interactive terms were statistically significant (Table 6).

The surface plots drawn for the two experimental high-capacity reclaimers' (3-saw and 700) process conditions of reclaimer speed and carryover/seed ratio helped to understand the interactive effect of these process variables (reclaimer speed and carryover/seed ratio) on the seed and lint loss per bale during the reclaimer process. The predicted data generated based on the 3-saw and 700 reclaimers for lint and seed loss per bale with both significant and non-significant terms in the models was further used for drawing the surface plots.

Table 5. Regression models for Upland and Pima cotton.

Upland			
3-Saw	**Models**	**Coefficient of Determination (R^2)**	**Statistical Significance**
Lint loss (kg/bale)	$31.257 - 1.7682x_1 + 0.0580x_2 + 0.02254x_1^2 + 0.00030x_2^2 - 0.00216x_1x_2$	0.99	$p < 0.01$
Seed loss (kg/bale)	$-303.693 + 22.960x_1 - 2.523x_2 - 0.276x_1^2 + 0.035x_2^2 - 0.052x_1x_2$	0.99	$p < 0.01$
700			
Lint loss (kg/bale)	$-9.70574 + 0.28600x_1 + 0.20322x_2 - 0.00192x_1^2 - 0.00086x_2^2 - 0.00265x_1x_2$	0.92	$p < 0.1$
Seed loss (kg/bale)	$186.1788 - 5.4589x_1 - 2.4221x_2 + 0.0788x_1^2 + 0.0174x_2^2 + 0.0024x_1x_2$	0.99	$p < 0.001$
Pima			
3-Saw	**Models**	**Coefficient of Determination**	**Statistical Significance**
Lint loss (kg/bale)	$0.112907 + 0.08943x_1 - 0.01212x_2 - 0.008781x_1^2 + 0.000113x_2^2 + 0.000397x_1x_2$	0.84	NS
Seed loss (kg/bale)	$-3.6399 + 11.1666x_1 - 0.149282x_2 - 0.78846x_1^2 + 0.00216x_2^2 - 0.05771x_1x_2$	0.99	$p < 0.01$
700			
Lint loss (kg/bale)	$9.87409 - 3.48437x_1 - 0.06947x_2 + 0.30383x_1^2 + 0.00010x_2^2 + 0.01380x_1x_2$	0.99	$p < 0.01$
Seed loss (kg/bale)	$-198.444 + 86.896x_1 + 0.755x_2 - 8.187x_1^2 + 0.001x_2^2 - 0.240x_1x_2$	0.99	$p < 0.0001$

Note: Carryover/seed ratio (%) (x_1), Reclaimer speed (Hz) (x_2).

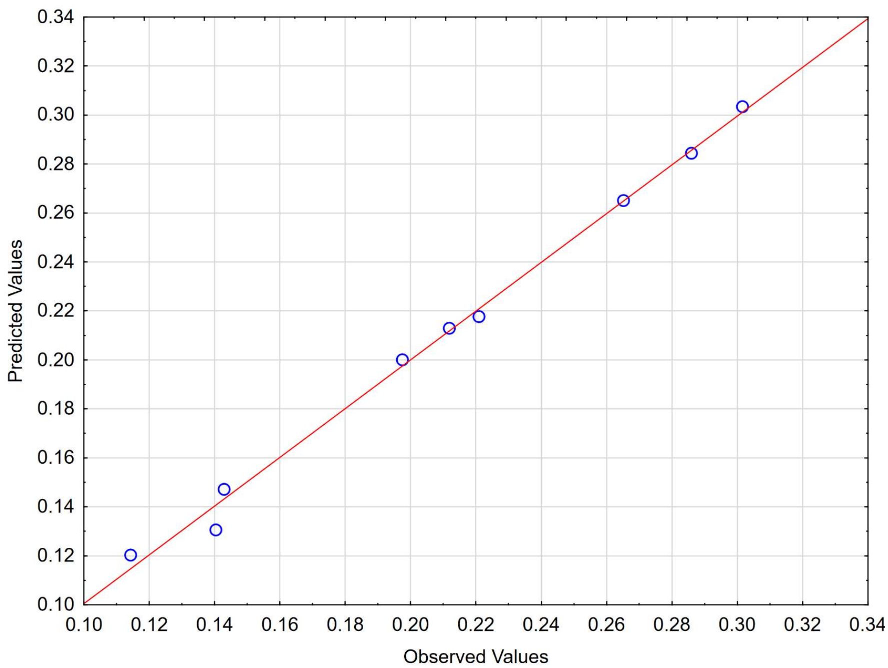

Figure 10. Predicted and observed plots for lint loss for Pima cotton with the 700 reclaimer.

3.2. Upland Cotton—Surface Plots

3.2.1. 3-Saw Reclaimer

The surface plot drawn for the 3-saw with Upland cotton indicated that the lowest lint loss value of <0.4 kg/bale was achievable at higher carryover/seed ratios of 35–37% and reclaimer speeds of 30–40 Hz (Figure 12). The maximum lint loss of >1.4 kg/bale was observed at a higher reclaimer speed and a lower carryover/seed ratio. The surface plot indicates that the carryover/seed ratio influenced the lint loss more than the reclaimer speed, which confirms the ANOVA results. In the case of seed loss, a higher reclaimer speed of >45 Hz reduced the seed loss to <22 kg/bale at the lowest carryover/seed ratio. Running the 3-saw reclaimer at 30 Hz at nearly all carryover/seed ratios (>32%) maximized the seed loss to >52 kg/bale (Figure 13).

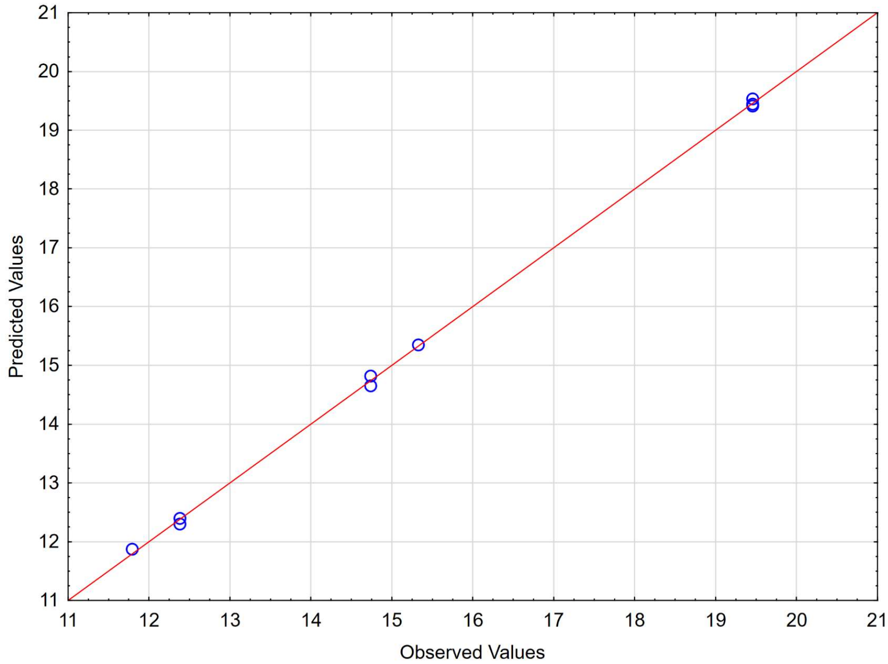

Figure 11. Predicted and observed plots for seed loss for Pima cotton with the 700 reclaimer.

Table 6. ANOVA table for RSM models developed for the 3-saw and 700 reclaimers.

Model Terms	**Upland Cotton**				**Pima Cotton**			
	3-Saw		**700**		**3-Saw**		**700**	
	Lint Loss	**Seed Loss**	**Lint Loss**	**Seed Loss**	**Lint Loss**	**Seed Loss**	**Lint Loss**	**Seed Loss**
Intercept	ns	ns	ns	ns	ns	ns	*	*
Linear								
x_1	*	ns	ns	ns	ns	ns	*	**
x_2	ns	ns	ns	ns	**	ns	**	*
Quadratic								
x_1^2	*	ns	ns	ns	ns	ns	*	**
x_2^2	ns	**	ns	**	**	ns	*	*
Interactive								
x_1x_2	ns	ns	ns	ns	ns	ns	**	**

Note: * significant at $p < 0.1$; ** significant at $p < 0.05$; ns = non-significant; x_1: carryover/seed ratio (%); x_2: reclaimer speed (Hz).

3.2.2. 700 Reclaimer

In the case of the 700 reclaimer, the seed and lint loss were different compared to the 3-saw reclaimer, and the trend of the process conditions was also different. The lowest lint loss observed was at a lower carryover/seed ratio of about 31% and a reclaimer speed of 30 Hz (Figure 14). On the other hand, increasing the reclaimer speeds to 50 Hz or higher increased the lint loss to >1.2 kg/bale (Figure 14) regardless of carryover/seed ratio. Reclaimer speed had a more prominent effect on the lint loss than the carryover/seed ratio as illustrated by the lint loss contour lines lying nearly parallel to the carryover/seed ratio axis. The seed loss observations for the 700 were opposite to the lint loss observations. Running the reclaimer at greater speed reduced seed loss. The minimum seed loss of <14 kg/bale occurred at the highest speed, whereas the maximum seed loss observed was >34 kg/bale at the lowest speed (30 Hz) (Figure 15). The surface plot also indicated that the carryover/seed ratio had very little impact on seed loss at any speed as similar to lint loss, the seed loss contour lines were nearly parallel to the carryover/seed ratio axis.

Additionally, the results indicated that the lint and seed loss were generally lower for the 700-reclaimer compared to the 3-saw reclaimer.

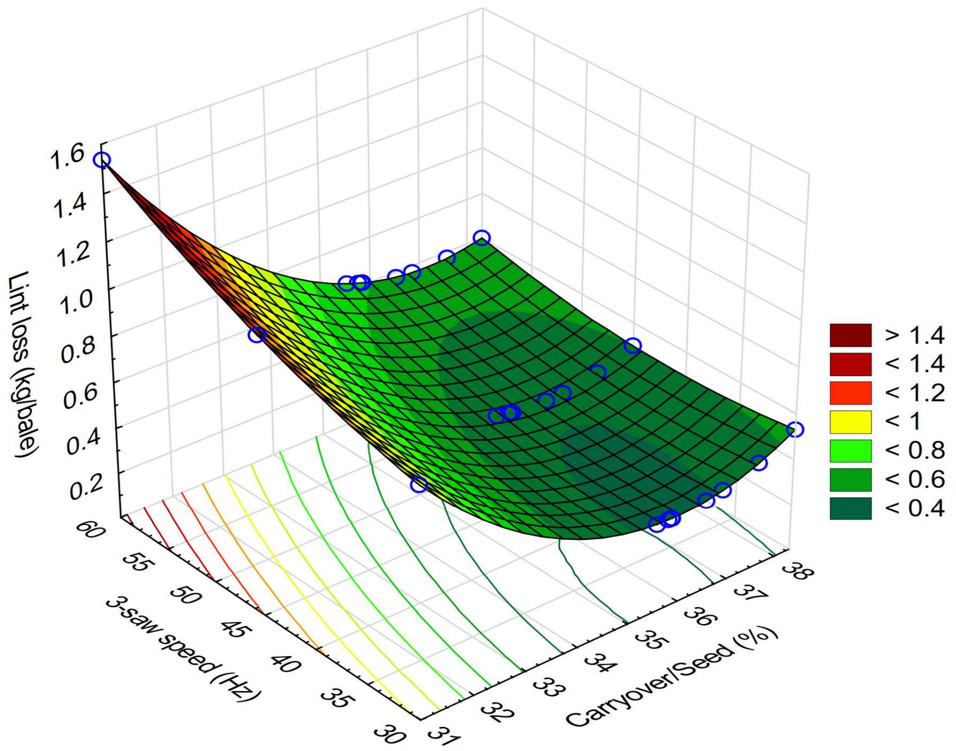

Figure 12. Lint loss for the 3-saw reclaimer with Upland cotton.

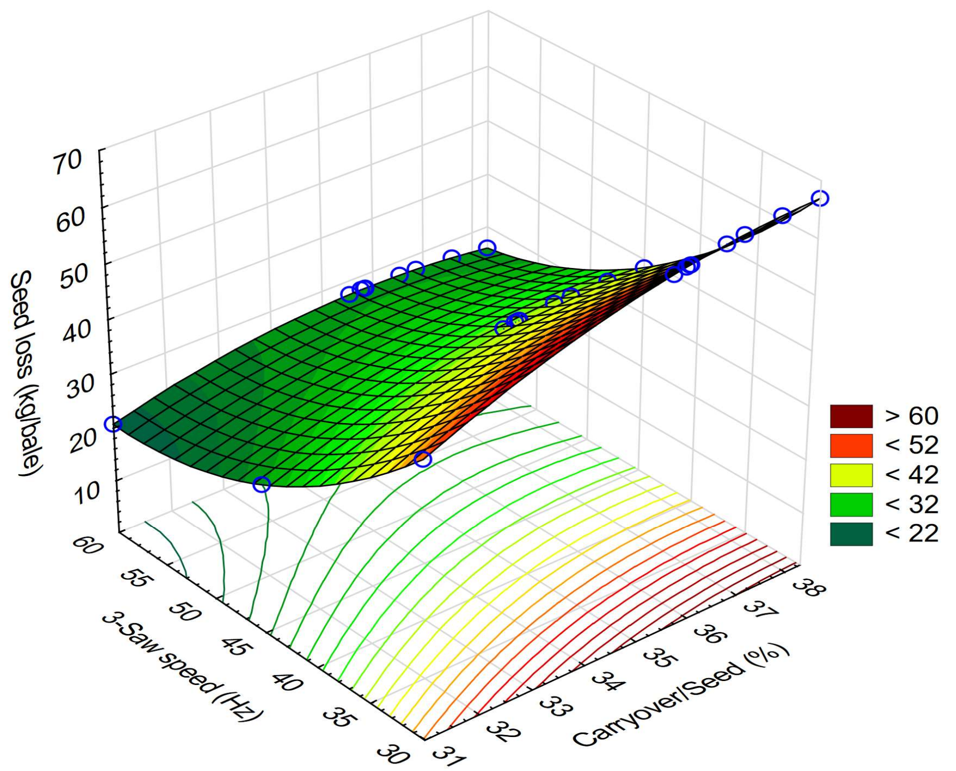

Figure 13. Seed loss for the 3-saw reclaimer with Upland cotton.

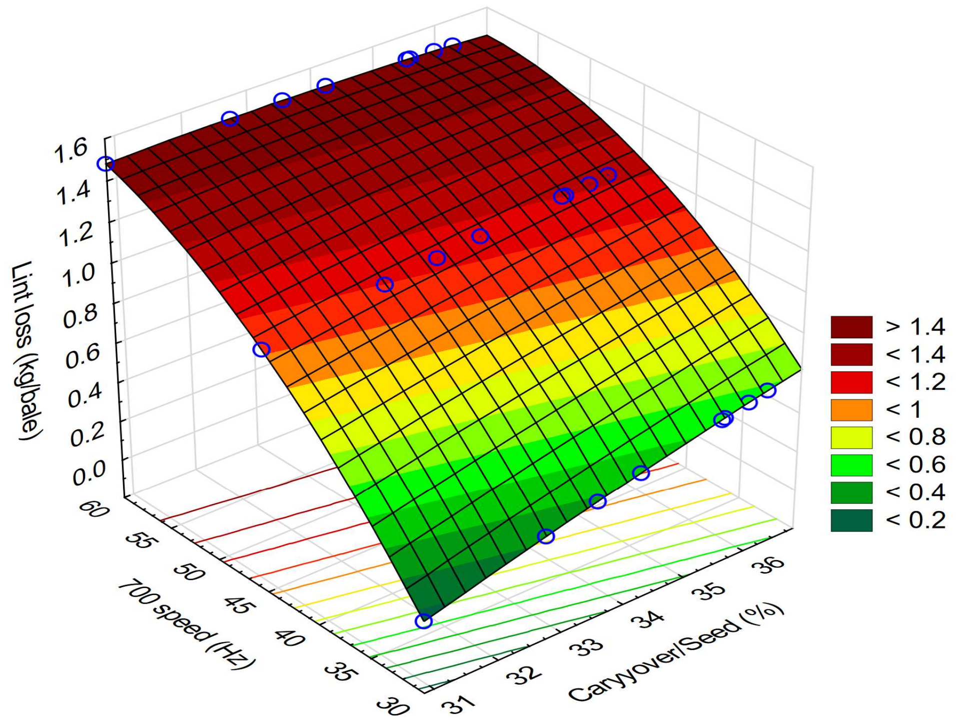

Figure 14. Lint loss for the 700 reclaimer with Upland cotton.

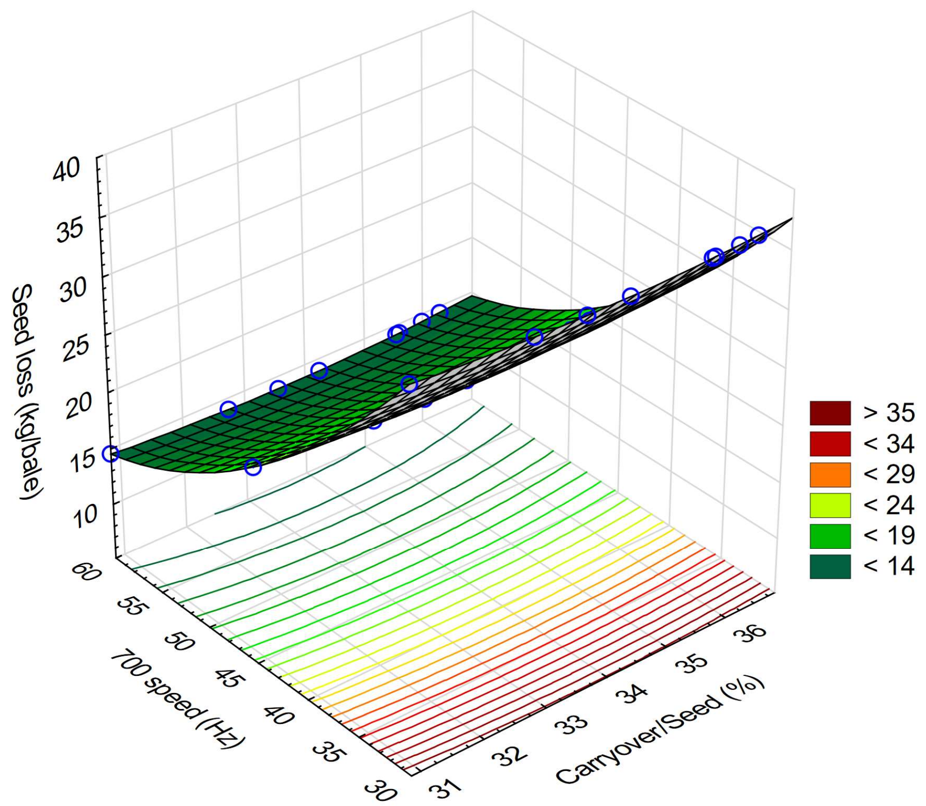

Figure 15. Seed loss for the 700 reclaimer with Upland cotton.

3.3. Pima Cotton-Surface Plots

3.3.1. 3-Saw Reclaimer

The surface plot for lint loss with the Pima cotton using a 3-saw reclaimer is shown in Figure 16. It is clear from the figure that the lint loss was minimized at a reclaimer speed of about 45 Hz, where increasing and decreasing the reclaimer speed increased the lint loss. The surface plot indicates that the reclaimer speed and carryover/seed ratio impacted the lint loss significantly. Additionally, the plot indicates that less lint loss occurred at lower carryover/seed ratios. The highest lint loss of >0.1425 kg/bale was observed at the reclaimer's full speed of 60 Hz and the highest carryover/seed ratio of 6%, whereas the lowest lint loss of <0.0925 kg/bale was observed at 3/4 (45 Hz) of the reclaimer speed and the low carryover/seed ratio (<4.4%). Figure 16 shows that seed loss is influenced more by reclaimer speed. The minimum seed loss (<13 kg/bale) was observed at the highest reclaimer speed and the maximum seed loss (>22 kg/bale) was observed at the lowest reclaimer speed. The carryover/seed ratio had less impact on seed loss as indicated by the surface plot (Figure 17).

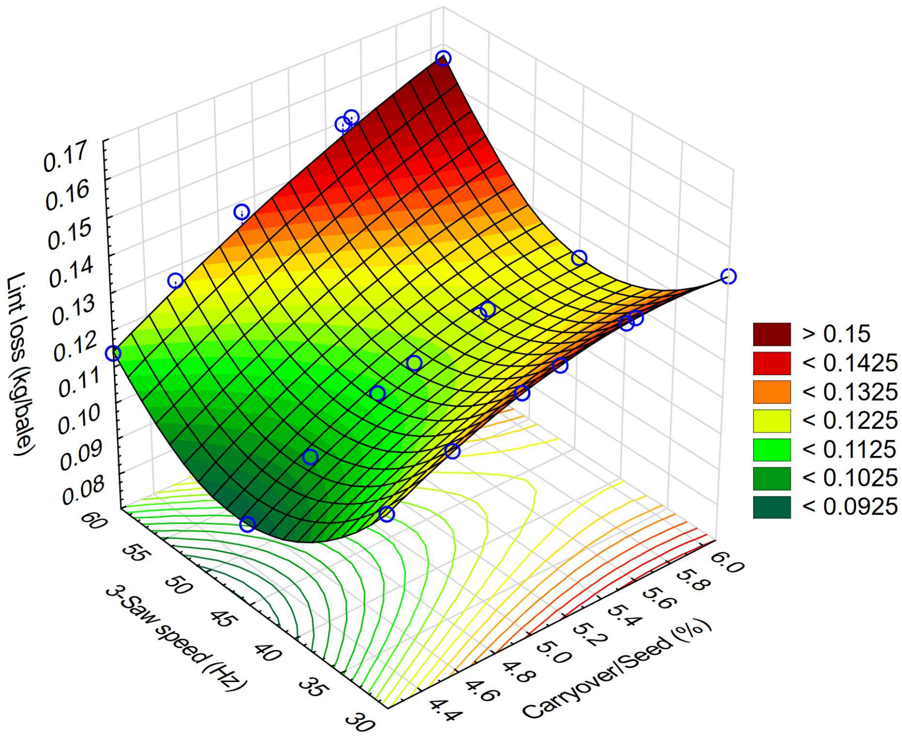

Figure 16. Lint loss for the 3-saw reclaimer with Pima cotton.

3.3.2. 700 Reclaimer

The 700 reclaimer resulted in marginally higher lint loss compared to the 3-saw (<0.0925 versus <0.12 kg/bale). The surface plot indicated that the carryover/seed ratio and reclaimer speed impacted the lint loss (Figure 18). In the plot, lint loss was represented as a valley with lowest values occurring for carryover/seed ratio >4.5% and reclaimer speed <45 rpm. The highest lint loss values (>0.32 kg/bale) were observed at the highest carryover/seed ratio of about 4.9% and higher reclaimer speeds of 50–60 Hz (Figure 18). The surface plot indicated that increasing reclaimer speeds increased the lint loss when carryover/seed ratios were >4.5%. In the case of seed loss, the lowest observed was <9 kg/bale, and the maximum was >18 kg/bale. Reclaimer speeds of >45 Hz minimized the seed loss, while carryover/seed ratio had a marginal effect on seed loss (Figure 19).

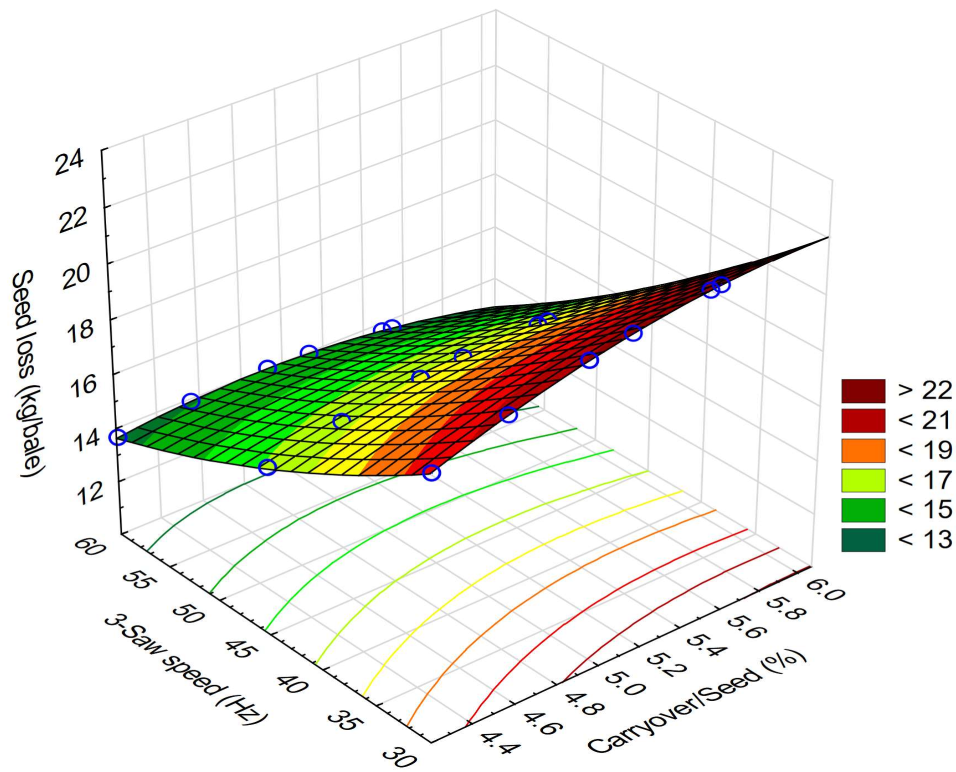

Figure 17. Seed loss for the 3-saw reclaimer with Pima cotton.

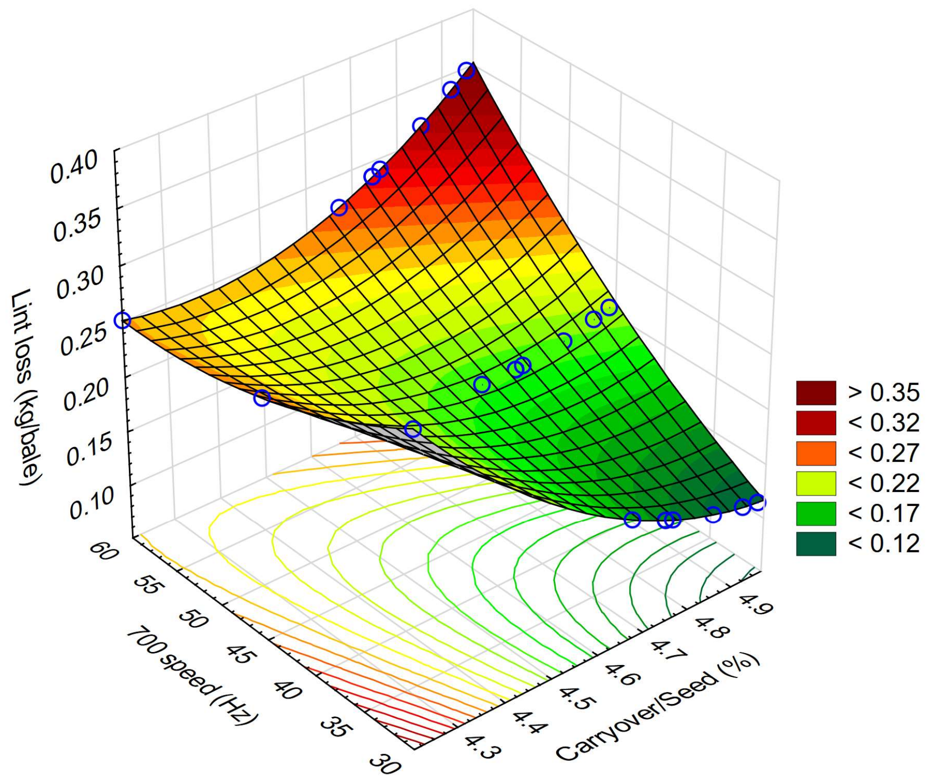

Figure 18. Lint loss for the 700 reclaimer with Pima cotton.

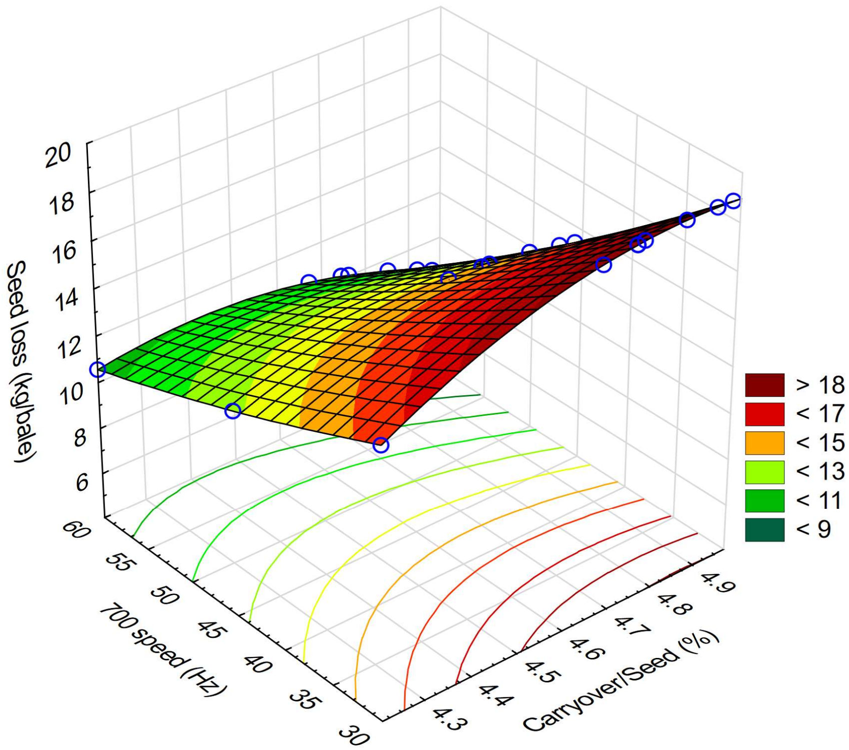

Figure 19. Seed loss for the 700 reclaimer with Pima cotton.

3.3.3. General Reclaimer Settings to Minimize the Seed and Lint Loss Based on Surface Plots

The trends of the surface plots indicated that for Upland cotton processed on the 3-saw reclaimer, to minimize the lint loss per bale, a carryover/seed ratio of about 35 to 37% and a low reclaimer speed (less than 40 to 45 Hz) was necessary. To minimize Upland seed loss with the 3-saw, a low carryover/seed ratio (31–33%) and high reclaimer speeds (50–60 Hz) was needed. In the case of the 700 reclaimer, lower to medium carryover/seed ratios (31–33%) and lower reclaimer speeds (30–34 Hz) minimized lint loss and a higher reclaimer speed of 50–60 Hz minimized the seed loss, regardless of carryover/seed ratio. In the case of Pima cotton with the 3-saw reclaimer, a lower carryover/seed ratio of about 4.6% or less and a medium reclaimer speed of 40–50 Hz minimized the lint loss. Seed loss was minimized with high reclaimer speeds of 50–60 Hz. For the 700 reclaimer, lower Pima lint loss occurred at lower reclaimer speeds (30–40 Hz) and higher carryover/seed ratios (4.6% and higher). Medium to high carryover to seed ratios (4.6–4.9%) and higher reclaimer speeds of 50–60 Hz minimized the seed loss.

3.4. Process Conditions Identified by HGA to Minimize the Seed and Lint Loss

With Upland cotton, the individual optimum process conditions identified using an HGA are given in Table 7. The table shows that a high carryover/seed ratio (35.97%) and a low reclaimer speed (32.43 Hz) for the 3-saw is desirable for minimum lint loss of about 0.38 kg/bale. However, a low carryover/seed ratio (31.21%) and a high reclaimer speed (about 60 Hz) minimized the seed loss. In the case of the 700 reclaimer, the observation was the opposite for carryover/seed ratio, whereas the observations for reclaimer speeds were similar. The lowest carryover/seed ratio and lowest reclaimer speed resulted in the lowest lint loss (0.19 kg/bale), whereas high reclaimer speed resulted in the lowest seed loss of about 13.90 kg/bale. Therefore, based on the optimized values, the 700-reclaimer resulted in lower Upland cotton lint and seed loss than the 3-saw reclaimer.

Table 7. Individual reclaimer process conditions optimized using a hybrid genetic algorithm to minimize the lint and seed loss.

Upland		**Minimum**	**Minimum**
x_1 (Carryover/Seed Ratio)	**x_2 (Reclaimer Speed, Rpm)**	**Lint Loss (kg/bale)**	**Seed Loss (kg/bale)**
3-saw			
35.97	32.43	0.38	
31.21	59.99		21.29
700			
31.24	30.08	0.19	
33.83	59.86		13.90
Pima		Minimum	Minimum
3-saw			
4.292	46.41	0.094	
5.904	59.80		13.22
700			
4.866	30.16	0.13	
4.965	59.99		8.58

In the case of Pima cotton, a medium reclaimer speed of about 46 Hz and the lowest carryover/seed ratio resulted in minimum lint loss of about 0.094 kg/bale for the 3-saw reclaimer (Table 5). Whereas a maximum carryover/seed ratio of about 5.9% and a reclaimer speed of about 60 Hz minimized the seed loss to about 13.22 kg/bale. In the case of the 700 reclaimer, a high carryover/seed ratio was necessary to minimize both the seed and lint loss, but the lowest reclaimer speed (30 Hz) minimized the lint loss (0.13 kg/bale), and the highest reclaimer speed (about 60 Hz) minimized the seed loss (8.58 kg/bale).

3.5. Process Conditions to Minimize Seed and Lint Loss in a Parallel Arrangement

Table 8 gives the optimized conditions for the 3-saw and 700 reclaimers in parallel for both Upland and Pima cotton. For the Upland cotton having 3-saw and 700 reclaimers in a parallel arrangement, a lower carryover/seed ratio and higher reclaimer speeds minimized the total (seed + lint) loss (22.35 kg/bale). For Pima cotton, higher carryover rates of about 6% were desirable for a 3-saw reclaimer to lower the total loss, whereas to lower the total loss (13.16 kg/bale) a lower reclaimer speed of about 30 Hz was desirable (Table 8). For the 700 reclaimer, a higher carryover/seed ratio of about 4.9% was desirable, and the higher reclaimer speeds of 60 Hz minimized the total loss to about 9.25 kg/bale.

Table 8. Process conditions to minimize the seed and lint loss for Upland and Pima cotton for the 3-saw and 700 reclaimers in a parallel arrangement.

Cotton Variety	**Carryover/Seed Ratio (%)**	**Reclaimer Speed (Hz)**	**Minimum Seed Loss (kg/bale)**	**Minimum Lint Loss (kg/bale)**
Upland				
3-saw	31.05	59.56	20.84	1.51
700	33.54	59.68	13.95	1.48
Pima				
3-saw	5.988	59.75	13.01	0.15
700	4.926	59.99	8.91	0.34

3.6. Economic Analysis

Table 9 indicates the economic loss in dollars per bale when the conventional and experimental high-capacity reclaimers were tested in the project under optimized conditions for seed and lint loss. In the case of Upland cotton, there was about $16/bale economic loss for the conventional reclaimer. Under the optimized conditions of minimum seed loss, the 3-saw resulted in an economic loss of about $8.63/bale, whereas under the optimized conditions for minimum lint loss, the economic loss was about $18.38/bale which is higher than the conventional reclaimer. In the case of the 700 reclaimer, the minimum $/bale loss of about 6.44 was observed under the optimized conditions of minimum seed loss (about 60% lower than conventional reclaimer), whereas at the optimized conditions of minimum lint loss, economic loss was about $11.58 per bale, which was lower than the conventional reclaimer. Therefore, the total economic loss was lowest for the 700, followed by the 3-saw and the conventional when the reclaimers were run at minimized seed loss conditions with Upland cotton. Based on $/bale loss calculated, the other possible scenario for minimizing the economic loss of Upland cotton can be running the two 700 reclaimers in parallel where the $/bale loss will be lower still ($12.88), compared to having two conventional or two 3-saw reclaimers in parallel ($32/bale for conventional and $17.26/bale for the 3-saw, respectively).

Table 9. Economic loss for 3-saw and 700 at minimum seed and lint loss process conditions in comparison to the conventional reclaimer.

Upland	Lint Loss (kg/bale)	Seed Loss (kg/bale)	Economic Loss ($/bale)
Conventional-Industry standard	5.63	24.37	15.97
3-Saw (minimum lint loss) (Table 7)	0.38 (minimum)	59.40	18.38
3-Saw (minimum seed loss) (Table 7)	1.46	21.29 (minimum)	8.63
700 (minimum lint loss) (Table 7)	0.19 (minimum)	37.68	11.58
700 (minimum seed loss) (Table 7)	1.48	13.90 (minimum)	6.44
3-Saw and 700-parallel arrangement (seed and lint loss) (Table 8)	2.99	34.79	15.03
Pima			
Conventional-Industry standard	0.69	4.32	3.44
3-Saw (minimum lint loss) (Table 7)	0.094 (minimum)	15.99	4.93
3-Saw (minimum seed loss) (Table 7)	0.15	13.22 (minimum)	4.30
700 (minimum lint loss) (Table 7)	0.13 (minimum)	18.99	5.92
700 (minimum seed loss) (Table 7)	0.35	8.58 (minimum)	3.59
3-Saw and 700-parallel arrangement (minimum seed and lint loss) (Table 8)	0.49	21.92	7.91

For Pima cotton, the conventional reclaimer resulted in the lowest economic loss ($3.44/bale) based on the seed and lint loss compared to the 3-saw and 700 reclaimers (Table 8). For the 3-saw, the lowest per bale loss observed was $4.30 when operating conditions minimized seed loss. In the case of the 700, the lowest observed loss was about $3.59/bale under the optimized conditions for minimum seed loss, which was close to the economic loss observed when a conventional reclaimer was used ($3.44/bale). Therefore, based on the economic analysis, running the conventional or 700 is desirable to minimize the economic loss, compared to the 3-saw with Pima cotton. The difference between conventional and 700 reclaimers was about $0.15/bale (Table 9) when the 700 was operated at the optimal conditions for minimum seed loss.

4. Discussion

A reclaimer is a specialized machine that returns carryover to the roller gin stand for re-ginning. The empirical data and models developed for the 3-saw and 700 reclaimers indicated that both reclaimer speed and carryover/seed ratio impact the seed and lint loss. The data indicated that the carryover/seed ratio was about six to seven times higher for Upland than Pima cotton (30–38% versus 4–6%, respectively). The amount of carryover is mainly impacted by how easily fiber is ginned from the seed, and the ginning rate. Pima cotton has a low fiber-to-seed attachment force compared to Upland. So, Pima fibers are more easily removed from the seed than Upland fibers and produce less carryover. Higher roller ginning rates result in slightly more cotton unable to be ginned due to increased congestion at the ginning point; this generates larger amounts of carryover.

The surface plots and statistical analysis indicated a good interaction between two process variables (carryover/seed ratio and reclaimer speed) regarding lint and seed loss during the reclaiming process. The models developed have adequately described the process. The optimization of the models developed for the two experimental high-capacity reclaimers using an HGA indicated that the 700 resulted in lower lint and seed loss compared to the 3-saw for Upland cotton (0.19 kg/bale of lint and 13.90 kg/bale of seed compared to 0.38 kg/bale of lint and 21.29 kg/bale of seed, respectively). Under the optimum operating conditions, the 700 had 46% lower lint loss and 30% lower seed loss than the 3-saw reclaimer. In the case of Pima, the 3-saw had 38% lower lint loss and 24% higher seed loss compared to the 700 under optimum operating conditions. Both 3-saw and 700 reclaimers performed better for Upland cotton than the conventional reclaimer, in most cases. The conventional reclaimer resulted in about 0.69 kg/bale of lint loss for Pima cotton, whereas the 3-saw and 700 resulted in lower lint loss (0.094 and 0.12 kg/bale). On the other hand, the seed loss was about two times higher for the experimental high-capacity reclaimers compared to the conventional reclaimer. This study indicated that despite the narrow range of carryover/seed ratios tested, this variable still significantly impacted the seed and lint loss during reclaiming.

Based on the present study, the 700 reclaimer was best suited for Upland cotton as it results in a minimum economic loss, whereas for Pima cotton, the conventional reclaimer currently used by the industry is the best, followed closely by the 700 high-capacity reclaimer. The surface plots have indicated that the carryover/seed ratios and reclaimer speeds for minimizing the lint and seed loss differ and also differ for the two cotton types tested. The difference is because Pima, *G. barbadense*, and Upland, *G. hirsutum*, are distinct species; Pima lint is easily removed from the seed all at once (resulting in naked seed), while some lint remains on Upland seed even after ginning (resulting in fuzzy seed).

According to Armijo et al. [7], the conventional reclaimer allowed more residual carryover to pass through with seed output, and the attached lint is lost with the seed. Based on these authors, experimental reclaimers were better at reclaiming carryover at slower speeds as they captured more seed with the reclaimed output and returned it to the gin stand feeder instead of losing the material with the feeder trash. These authors reasoned that the residual fibers attached to the seed cling to the reclaimer saws better at slower speeds. This material is lost easily at higher speeds due to greater centrifugal force. Among the two cotton types tested, this effect was more pronounced for Upland cotton as it has more carryover than Pima. This is evident from the carryover/seed ratios, which were 30–38% for Upland and 4–6% for Pima cotton. The lower carryover rates for Pima cotton can significantly affect the performance of the two experimental high-capacity reclaimers. Testing these two experimental high-capacity reclaimers at wider carryover/seed ratios or at higher roller ginning rates is critical to understanding these two systems' performance more deeply. According to Armijo et al. [7], sending less carryover material to a conventional reclaimer resulted in less residual carryover material passing through to the seed output, resulting in less impact on its combined value of seed and lint loss. Less carryover material explains why less lint loss was observed for the conventional reclaimer for the Pima cotton. In the case of Upland cotton with higher carryover rates, the conventional reclaimer resulted in more lint lost in the waste stream. In the present study, the conventional reclaimer was operated at normal saw cylinder speed, as practiced by the industry; perhaps operating the conventional reclaimer saws at different speeds could optimize performance. The economic loss in $/bale was higher for the conventional reclaimer than the experimental high-speed reclaimers when testing Upland cotton. In contrast, the $/bale loss for Pima was lower for the conventional compared to the two other reclaimers due to higher Upland lint loss and lower Pima seed loss. Future work aims to validate the results by conducting tests with the experimental reclaimers at the optimized conditions and testing the process in a parallel arrangement. Additionally, more work is planned to understand how ginning rates impact the carryover/seed ratios and performance of the two experimental high-capacity reclaimers. It is hoped that further tests will elucidate whether high-capacity experimental reclaimers can replace the conventional reclaimer currently used by the industry, and if they can reduce seed and lint loss, improving high speed roller ginning economics.

5. Conclusions

The following conclusions were drawn based on the present study:

- Response surface models developed adequately described the reclaiming process based on the coefficient of determination values of >0.84, and all the models were found to be statistically significant except the lint loss model for the 3-saw reclaimer.
- The surface plots indicated that reclaimer speed had a more prominent effect on the lint and seed loss than the carryover/seed ratio. Even though the carryover/seed ratio tested was narrow, it still impacted the lint loss for both 3-saw and 700 reclaimers.
- For 3-saw, higher carryover/seed ratios and lower reclaimer speeds, and for 700, lower carryover/seed ratio and lower reclaimer speeds are necessary to minimize the lint loss, whereas for seed loss, carryover/seed ratio did not have much impact, but higher reclaimer speeds reduced the seed loss.
- For Pima cotton, both 3-saw and 700 reclaimers need to be operated at lower reclaimer speeds to minimize the lint loss; in the case of seed loss, the carryover/seed ratio had a marginal effect, whereas higher reclaimer speeds reduced the seed loss.
- Under the optimized process conditions, 700 reclaimer is the best for Upland and Pima cotton compared to the 3-saw reclaimer. Compared to the conventional reclaimer used by the industry, the 700 minimized the seed and lint loss for Upland cotton, whereas the conventional performed better for Pima cotton.
- The economic loss based on the lint and seed loss while reclaiming Upland carryover indicated that the 700 reclaimer resulted in 40% as much loss (6.44 versus 15.97 $/bale) than the conventional reclaimer. In the case of Pima cotton, the conventional reclaimer performed better than the 700 reclaimer by lowering the seed loss and further reducing the economic loss (3.44 vs. 3.59 $/bale).

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Data Availability Statement: The data presented in this study is based on experiments conducted by Armijo et al. [7].

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

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