

Evaluation of a low-cost selective shaking device and soft surface catchment for fresh market blueberry harvesting

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Abstract—With the surge in global blueberry consumption, there is a growing need for efficient harvesting methods to meet market demands. Traditional hand harvesting remains the norm for fresh market blueberries, but it is labor-intensive and costly. This paper presents a feasibility study of a cost-effective human-assisted mechanical harvesting system designed for tunnel-grown blueberries. The system incorporates lightweight, battery-powered hand-held shakers and multi-level soft surface catchers operating in tandem. Performance evaluation compared traditional hand-harvesting with the proposed system in terms of post-harvest quality and harvest rate. Results indicate that the proposed system offers a higher harvest rate (81.3 berry per minute) but may yield more unripe berries (30.6%). Optimization of detachment settings at 900rpm for 1.2s, shows potential to improve system performance up to 80.7%. Overall, the study highlights the effectiveness of the human-assisted approach in bridging the gap between manual and machine harvesting, with implications for enhancing efficiency and reducing labor costs in the blueberry industry.

I. INTRODUCTION

Blueberries have become one of the most sought-after fruits globally, experiencing a surge in consumption over the past five years and securing their position as the second most significant soft fruit species, trailing only strawberries [1]. In New Zealand, the land area dedicated to blueberry cultivation has steadily increased since 2011, reaching 787 hectares in 2022 [2]. The number of orchards adopting tunnels to grow blueberries is also increasing. There is a rising demand for Machine Harvesting (MH) in the blueberry industry to enhance efficiency, reduce labor expenses, and mitigate issues related to harvest-induced losses. Blueberries grown for processed markets, such as frozen or juiced, are often machine-harvested as harvest-induced loss or damage is of little concern. However, fresh market requirements are more stringent, and further research and development into MH is required. The delicate nature of blueberry fruit, the current plant architecture, and the unpredictable ripening window pose significant challenges to the mechanization and automation of blueberry harvesting. Tunnel-grown blueberry has better fresh market quality and yield due to better nutrition intake and climate control, however, the tunnel structures also limits the adaptation to MH.

Recent studies by DeVetter et al. [3] have demonstrated that the quality of mechanically harvested fresh market

blueberries can be improved using a modified over-the-row (OTR) harvester by replacing the catchment surface with neoprene. Despite these positive findings, many orchard owners remain hesitant to invest in MH due to uncertainties surrounding the economic feasibility and viability of adopting mechanical harvesters. With an approximate cost of US\$240,000 per unit of OTR harvester, this technology remains financially out of reach, particularly for smaller blueberry orchards spanning less than 10 hectares [4].

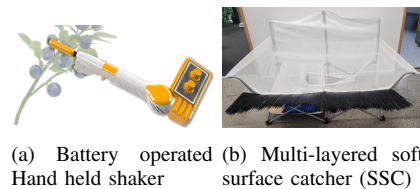


Fig. 1: Proposed Human-assist mechanical harvesting system

This paper assesses the feasibility of a cost-effective human-assisted mechanical harvesting system (Fig.1) developed by Sim et al. [5] on tunnel grown blueberries. The aim is to bridge the gap between large and expensive over-the-row (OTR) harvesters and traditional hand harvesting methods, particularly for smaller fresh market blueberry orchards. The proposed system comprises a pair of low-cost, lightweight, battery-powered, hand-held shakers (see Fig. 1a) and multi-level soft surface catcher (SSC) (see Fig. 1b), operating in tandem. The shakers detach blueberries by applying reciprocating movements to the branch (cane) adjacent to the berry cluster.

The objectives of this evaluation were to (i) compare the post harvest qualities and rate of harvesting by hand, with or without SSC, and hand-held shaker with SSC, (ii) identify the range of optimum harvest settings for the shaker.

II. BACKGROUND AND RELATED WORK

The agricultural sector is actively embracing technological advancements to boost the blueberry industry, focusing on both export and local fresh-market blueberries [6]. Amidst the global increase in harvesting costs and a shortage of skilled labor [7], ongoing efforts are essential to explore and optimize mechanical harvesting methods for blueberries. This exploration should consider factors such as fruit quality, harvest efficiency, and the distinct requirements of different blueberry cultivars [8].

With blueberries ripening successively, indicators like ease of removal, consistent color, and taste determine harvest readiness [9]. Harvesting occurs over multiple cycles within

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1-3 months, emphasizing the importance of removing ripe berries while leaving unripe ones for subsequent cycles. Selective mechanical harvesting of only ripe blueberries is gaining significance to enhance the yield of ripe berries in each harvest cycle.

A. Autonomous Mechanised Harvesting

Selective harvesting fruit crop requires reasonably skilled labour. While machines can handle much of the physical work, producing a machine vision system capable of accurately assess and locate ripe fruit remains a challenge. This is particularly complex for blueberries due to their dense clustering and occluded growing environment [10]. Various technologies and methodologies have been explored for ripe berries detection, including deep learning [11] [12], hyperspectral imaging [13] [14], non-destructive detection methods [15], and electronic nose technology [16].

Deep learning has demonstrated the potential to detect blueberries in their natural environment and predict their quality before harvest. However, ongoing research is needed to reduce network parameters and enhance detection capabilities [10] [17]. The nuanced changes in the average RGB value of blueberry skin often serve as an indicator of berry maturity. However, these changes can be influenced by shifting ambient lighting conditions, diseases, occlusion, bloom, cultivar differences, and other variables. Controlled lighting, substantial processing power, and high-resolution image sensors, are crucial for detection accuracy. Fortunately, various improvements can be implemented to reduce dependence on machine vision.

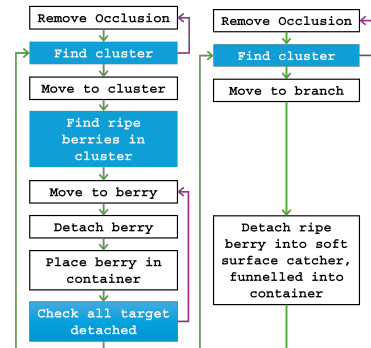
B. Human-Assist Harvesting

The demand for small scale harvesting system has driven research towards the development of hand-held shakers and portable SSC for blueberry harvesting. This systems rely on human vision to locate fruit.

Research by Takeda et al. [4] utilized a hand-held, pneumatic olive shaker (Golia model) targeting multiple branches simultaneously, coupled with portable SSC. The system harvested significantly more fruit than manual harvesting, and soft fruit-catching surfaces reduced impact force and bruise damage. Ergonomic analysis by [18] emphasized the importance of reducing tool weight and transmission of vibration to operator’s hand. The platform 2 persons to manually maneuver or towed behind a tractor. This semi-mechanical harvesting platform (BBC Technologies, Fresno, CA, USA) cost at least \$11,000 each not including modification to suit tunnel structures. Starberry MD2 developed and patented by Campagnola, Italy [19], claimed to be the first handheld electric hook shaker for bilberry and small fruit harvesting, it resembles a battery hand drill. Frequency of the oscillation and timing are determined by the operator, with SSC as an add-on accessories.

A previous study by Sim et al. [5] indicated that the detachment force to remove blueberries from their pedicel does not clearly define ripe and unripe berries. However,

selective harvesting mechanically is possible using a hand-held shaker targeting a single cluster at a time, although further ergonomic improvements and shaking speed refinement are necessary. Figure 2 illustrates the workflow of two autonomous harvest approaches. Figure 2a requires machine vision for maturity evaluation, accurate positioning, and harvest feedback. In contrast, the figure 2b necessitates only approximate positioning of clusters with machine vision when using a mechanical selective harvesting end effector with position tolerance, making harvesting more straightforward and achievable.



(a) Machine Vision (b) Mechanical selective harvest

Fig. 2: Comparing two autonomous harvest approaches, text box in blue indicates the implementation of machine vision

C. Harvest Induced Loss

The quality of machine-harvested blueberries is a critical consideration, with studies comparing post-harvest quality between mechanically and hand-harvested blueberries, revealing differences in firmness, appearance, and weight loss during storage [3] [20]. Post harvest firmness is particularly vital as it indicates fruit quality, transportability, and shelf life. Harvested blueberries are graded by either humans or commercial grading machines into marketable grades and rejects, based on physical properties. Grading outcomes are influenced by harvest treatment, orchard management, post-harvest logistics, growing environment, and various other factors. Common harvest-induced reject attributes include under-ripeness (3a), bruises and splits (3b), beard retention (3c), pedicel retention (3d), and lack of bloom (3e). Attributes such as dehydration, irregular shapes, blemishes and spots, insects and diseases (3f), softness, and undersized, are influenced by the aforementioned factors. Beard retention is typical problem for blueberries grown in tunnels.

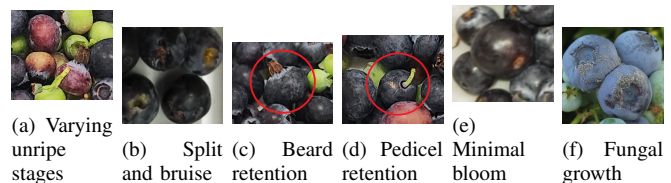


Fig. 3: Common blueberry reject attributes

III. IMPROVED HARVEST SYSTEM PROTOTYPE

The previous harvest system studies conducted by Sim et al. [5] featured a hand-held shaker with 2 prongs for applying reciprocating motion to individual branches, alongside an SSC. The shaker prototype utilized a Makita DHP482STX9 with a modified reciprocating saw adaptor for hand drill, while the catcher comprised whitebait polyester mesh attached to an aluminum extruded frame. For this evaluation, enhancements were made. The redesigned shaker prototype weighs 175g and features a 20mm stroke length, with the battery relocated to the belt for improved balance and reduced Risk of Strain Injury (RSI) for the user. The modified SSC weighs 5.6kg, with dimensions of 1560mm span and 580mm depth. It utilizes a modified 2-person camping chair frame and a 3-stage polyester netting funnel suspended from the frame to gently guide berries into the harvest container. The polyester netting, commonly used in whitebait fishing, is robust, soft, food-safe, and easy to clean. Additionally, 300mm wide extruded flexible back strip brushes are employed to reduce ground loss. The shaker's speed is adjustable by the user using a sliding potentiometer, targeting individual clusters (canes) for harvesting. Cost of manufacturing a whole set of harvesting system, which consists of two shakers and two SSC, including material and time is approximately US\$2,200.

IV. PERFORMANCE EVALUATION

The harvest system's performance is evaluated based on post-harvest quality and harvest rate comparison of three treatments, (a) traditional hand-harvesting into bucket method (HB), (b) hand harvesting into SSC (HC), and hand-held shaker harvesting into SSC (SC). The qualities concerned are firmness, shelf life, colour(ripeness), bruises, splits, beard and pedicel retention, and dehydration. Other controlled variables are (i) cultivar, growing location and setup, (ii) operators, (iii) sample collection and post harvest treatment, (iv) harvest timing.

1) *Cultivar, growing location and setup:* Masena, a SHB (Southern Highbush) cultivar developed by Mountain Blue Farms Pty Ltd (MB) [21], is chosen for the evaluation. This mid-season variety exhibits a relatively low detachment force of 0.5-1.0N [5]. Six Masena bushes, cultivated in a greenhouse tunnel from an orchard in Pukehina, New Zealand, were selected to assess the performance of the harvest system.

2) *Operators:* For consistency, two relatively inexperienced operators are employed in all harvests. The operators work in tandem on either side of the bush.

3) *Sample collection and post harvest treatment:* Two bushes, A and B, are designated for each harvest treatment. operators are instructed to remove all ripe berries from the bush. Sample A, collected from bush A, is not timed to allow operators to familiarize themselves with the harvest treatment. Sample B, collected from bush B, is timed, and $T_{Harvest}$ is recorded. A total of 6 samples are collected at each trial. Sample A undergoes post-harvest firmness and shelf life evaluations, while Sample B is transferred to a

commercial cool store at 4°C and 95% humidity for three days. Afterward, it is graded using a commercial blueberry sorting machine. The setup time for all harvest treatments is not considered in this evaluation.

4) *Harvest Timing:* The number of ripe berries presents on the bush increase as the season progress. Trials were conducted on three separate days during the harvest window: the third week (E), sixth week (M), and ninth week (L) from the first day of the harvest window.

A. Post-Harvest Firmness and Shelf Life

Berries from Sample A are visually graded into marketable and rejects, with rejects being discarded. Two lots of 90 berries each were randomly selected for each harvest treatment. One lot is designated for firmness evaluation, while the other undergoes shelf life assessment.

1) *Firmness Evaluation:* Individual firmness was measured on the Shore A hardness scale using a non-destructive hand-held Durometer, as depicted in Figure 4. Samples were discarded after the evaluation.



Fig. 4: Turoi 53215BE, a Non-destructive measurement of the firmness of soft fruit

2) *Shelf Life Assessment:* 90 berries from each treatment and each harvest timing, divided and stored in three clam shell punnets, total of 810 berries for the whole assessment. The punnets were stored at 12°C with high humidity for 20 days to simulate the conditions of a supermarket fresh produce shelf. Samples were checked regularly for signs of mold or breakdown, with any moldy berries removed and discarded from the punnet as they occurred.

B. Post-Harvest Grading

Sample B was evaluated three days after harvest using a commercial blueberry sorting machine, KATO260 (5), developed by TOMRA and BBC Technology. This machine, equipped with multiple RGB and IR sensors, user-defined metrics, and machine learning and grading algorithms, eliminates subjectivity associated with human-led grading. The KATO260 appraises each berry into several grades, providing a more objective and consistent assessment.

1) *Grading metrics from KATO260:* In this paper, the focus is on reject attributes influenced by harvest treatment, such as ripeness, firmness, dehydration, beard & pedicel retention, bruises & splits, excluding bloom retention due to inconsistent bloom data from KATO260. Table I outlines the attributes of interest and their approximate acceptable limits as applied by the pack house. It is important to note that these limits are not standardized across the industry and vary between pack houses, harvest locations, seasons, cultivars, and the quality and quantity at the time of grading.



Fig. 5: KATO260 and LUCAi™, developed by BBC Technology, a popular blueberry sorting machine utilised by pack houses in New Zealand

Additional metrics output from the grading machine for each

TABLE I: Minimum metrics of Marketable Berries

Marketable Quality Metrics	MIN
Red Spot & Red Coverage	25%
Green Spot & Green Coverage	20%
Brown Spot & Beard	5%
Stem Protruding	40%
Bruise Size & Bruise Coverage	20%
Split Size & Coverage	45%
Dehydration	95%
Firmness (0-70)	20

treatment included the number of berries harvested ($N_{overall}$), marketable berries ($N_{marketable}$), unripe berries (N_{unripe}), damaged berries (N_{damage}) for each treatment.

2) *Harvest Rate*: The overall harvest rate ($\hat{H}_{overall}$) of each treatment are one of crucial metrics to evaluate the harvest performance.

$$\hat{H}_{overall} = \frac{\sum N_{overall}}{\sum T_{harvest}} \quad (1)$$

C. Mechanical Detachment Settings Estimation

The removal of unripe blueberries from the bush can significantly impact future harvest yields, while failure to harvest all ripe berries may result in overripe, dehydrated, or soft berries being left for future harvests. Therefore, it is crucial to minimize both instances by optimizing the detachment settings.

Although there isn't a distinct detachment force between ripe and unripe berries, ripe berries generally require less input energy to detach compared to unripe ones. Input energy is correlated with reciprocating speed in rpm (RPM_{shake}), and application time in seconds (T_{shake}), with a fixed stroke length of 20mm for this evaluation.

A comprehensive evaluation involved testing each unique combination of RPM_{shake} (800, 900, 1000, 1100) and T_{shake} (1.0, 1.5, 2.0) on four clusters. A total of 48 clusters of Masena were randomly selected and tested during the ninth week of the harvest window. For each test, the number of berries (blue, red, and green) on the cluster was visually noted before harvest (B_i, R_i, G_i), after harvest (B_f, P_f, G_f), and the number of berries collected in the catcher (B_h, P_h, G_h).

The performance of the shaker and the harvest system is assessed through three calculated metrics: Detach Accuracy (DA), Detach Efficiency (DE), and Harvest Efficiency (HE). DA measures the ability of shaker to detach only ripe berries,

DE measures the ability of shaker to detach all ripe berries, and HE assesses the efficiency of the SSC capturing all the berries.

$$DA = (P_f + G_f)/(R_i + G_i) \quad (2)$$

$$DE = (B_i - B_f)/B_i \quad (3)$$

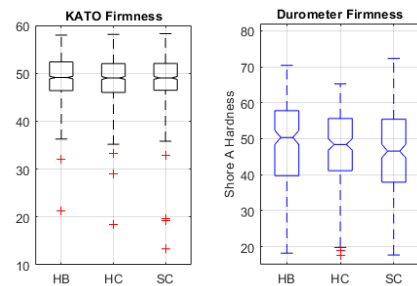
$$HE = B_h/((B_i + R_i + G_i) - (B_f + P_f + G_f)) \quad (4)$$

V. PERFORMANCE RESULTS

In this evaluation, Sample B data from the early harvest timing is omitted due to orchard management error, the berry bushes were harvested 3 days, instead of 7 days prior to the planned trial. Resulted in unusually high percentage of unripe fruit in all three treatments.

A. Sample A Firmness Evaluation

The firmness data output from KATO260 is unitless, while TR Turoni 53215BE can measure within the Shore A Hardness Scale range of 0 to 100. Blueberries with a firmness of 44A and below are categorized as soft, 45A to 65A as medium, and 65A and above as firm. The boxplot of KATO260 firmness (see Figure 6a) displays equal medians of 49 across three treatments. In contrast, the firmness boxplot of the durometer (see Figure 6b) reveals the highest medians of 50A for HB, marginally lower but not significantly different for both HC (48A), and SC (47A). While 90 berries were measured for both early and mid-harvest, only 30 berries were measured for late harvest as durometer has punctured the skin in many occasion, rendering the measurement unusable. Despite this, the treatment and timing of harvest did not appear to significantly affect berry firmness. Nevertheless, there are concerning instances of low firmness measurements across all treatments even before grading.



(a) Firmness measured with KATO260 (b) Firmness measured with Durometer

Fig. 6: Measured firmness of Masena with two different methods

B. Sample A Shelf Life Assessment

Out of the 270 berries in each treatment, only one berry was removed from both HB and HC due to mould and breakdown over the course of 20 days of shelf life assessment, while four berries were removed from SC. Despite having thinner skin and lower average firmness, these findings suggest that Masena exhibits significantly lower susceptibility to post-harvest breakdown and mould.

TABLE II: Mouldy Berries Removed

Treatment	Days after Harvest						Total
	3d	6d	10d	14d	17d	20d	
HB	0	0	1	0	0	0	1 (0.4%)
HC	0	0	0	0	0	1	1 (0.4%)
SC	0	1	1	1	0	1	4 (1.5%)

C. Sample B Reject Analysis

After graded with KATO260, data of each individual berry in Sample B are sorted into marketable and rejects. Table IV shows the total number of berries evaluated. Berries rejected for each treatment are classified based on their reject attributes, and some berries may have more than one attribute. Table III presents the number of each attribute among the rejected berries. The majority of the rejected berries are unripe, with significantly higher count of split and brown spot or beard retention in HB. SC has more instances of pedicel retention, dehydration, and softness. Some rejects may have more than one reject attributes.

TABLE III: Rejects Analysis of three treatments

	HB	HC	SC
Total harvested	1128	910	782
Unripe	156	199	239
Ripe but damaged	20 (2.06%)	8 (1.13%)	11 (2.03%)
Brown/Beard	4	1	1
Pedicel	1	1	5
Bruise	2	3	2
Split	13	3	2
Dehydration	0	0	1
Soft	0	0	2

D. Harvest Rate

$\dot{H}_{overall}$ of SC is the highest, followed by HC and then HB, as shown in Table IV. However, the percentage of unripe berries is also the highest at 30.6% for SC. Both HB and SC have higher overall percentage of damage compared to HC.

TABLE IV: Average harvest rate of each harvest treatment (berry/minutes) and percentage of marketable, unripe and damage

Treatment	$\dot{H}_{overall}$	Percentage		
		marketable	unripe	damage
HB	71.8	84.4%	13.8%	1.8%
HC	80.8	77.3%	21.9%	0.9%
SC	81.3	68.0%	30.6%	1.4%

E. Optimum Detachment Settings

The optimal detachment settings for each metric, namely DA, DE, and HE, were determined through multi-variable regression analysis. Introducing a new metric, harvest performance (HP), involved the multiplication of DA, DE, and HE with equal weighting to streamline the optimal detachment settings for the entire system, as all three metrics are equally important. Contour plots displaying all four metrics, with a common x-axis (RPM_{shake}) and y-axis (T_{shake}), as illustrated

in Fig.7. Across all four metrics, a preference for lower T_{shake} was evident, and both DA and HE exhibited improved performance at lower RPM_{shake} . The optimal detachment settings for harvesting Masena were identified as 900rpm for 1.2s, resulting in a HP score of 80.7%.

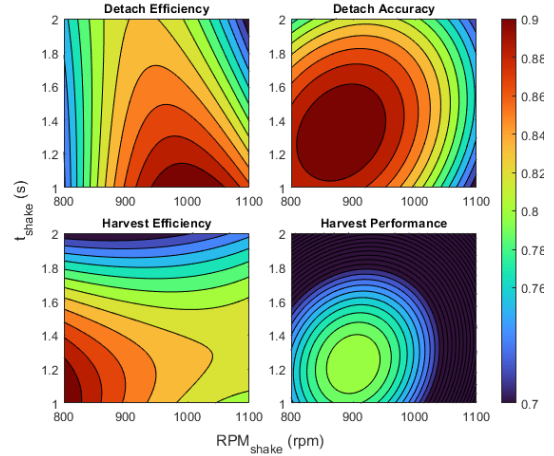


Fig. 7: Harvest Performance of the selective harvest system

VI. DISCUSSION

The firmness evaluation of both sample A and sample B indicated that neither the harvest treatment nor timing affected berry firmness, suggesting minimal impact damage across all three harvest treatments. A higher presence of unripe berries was observed in SC and HC due to the soft surface catchers successfully capturing nearly every detached berry. SC's lower marketable harvest rate was due to reliance on operator feedback and timing for shaking adjustments. Yet, with optimized detachment settings and operator experience, SC's rate is expected to improve, nearing human levels. It is noteworthy that regardless of operator experience, unconscious filtering of undesirable berries still occurred with HB and HC. Additionally, the total berry harvested was greatly affected by the number of berries present on the bush before harvest. The bushes reserved for SC yielded significantly fewer berries compared to those reserved for HB and HC, resulting in a substantial difference in total berry harvested. The harvest rate of SC (81.3 berry/min) surpassed that of HB (71.8) and HC (80.3), but it also has 13.8% more unripe berries and 0.4% less damaged berries compared to HB. HC exhibiting the least damage berries among the three (0.9%). This suggests that the soft surface catchers improve the post-harvest quality of blueberries. Operators expressed a preference for HC as they were not required to squat or kneel on the ground to reach the lower-hanging berries, less effort to prevent berries dropping onto ground. Preset detachment setting is preferred for human assist system, however, for future autonomous application, a closed loop system could be used with autonomous application where machine vision is used to control shaking time by tracking the detachment of ripe and unripe berries. Bloom retention was not investigated in this study due to the lack of a reliable evaluation method

for bloom before and after harvest. Further economic analysis would require long term study of the device in use within orchard environment.

VII. CONCLUSIONS

In summary, the comparison between the SC and HB revealed several key findings. SC demonstrated a higher berry harvest rate per minute (81.3) compared to HB (71.8), indicating its potential for improved efficiency in blueberry harvesting. The findings of this study underscore the effectiveness of the soft surface catchers (SSC) in capturing detached berries, resulting in a higher presence of unripe berries in the SC and HC treatments. Despite the lower marketable harvest rate observed in SC due to its reliance on operator visual feedback, optimization of detachment settings holds promise for improving this rate to approach human performance levels. Notably, unconscious filtering of undesirable berries during harvesting with HB and HC, highlights the need for further refinement in harvesting methods. Operators' preference for HC, attributed to its ergonomic advantages, highlights the importance of considering practical aspects such as ease of use and operator comfort in designing harvesting systems. It's important to note that human-assisted harvest systems may not completely replace experienced labor at this stage. Nevertheless, they hold promise in expanding the labor force demographic by reducing the physical and mental demands of the task. Furthermore, integration of the mechanical shaker-catcher system with machine vision technology could pave the way for fully automated harvesting systems operating beyond conventional hours, such as during nighttime. Future research endeavors should extend the evaluation of the system to include factors like setup time, increase sample size, trial frequency, and ergonomic assessments of operators. Additionally, assessing bloom retention with different surface materials of SSCs will be crucial for determining the most suitable catchment surface. The performance of the SSC is confirmed with randomized controlled trial, however, a systematic review of the SSC parameters in the future is essential to further advancements in blueberry harvesting technology and enhance overall efficiency and quality in the industry.

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