

Study of finger-star disc working tools of an inter-row cultivator

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Abstract. This study combines laboratory force-deflection characterization, tomato transplant pull-out measurements and a descriptive field verification of an inter-row cultivator equipped with polyurethane finger-star discs. The objective was to relate finger hardness to crop mechanical resistance and thereby define a practical screening criterion for reducing crop damage. Discs with hardness values of 73, 83 and 93 Shore A were loaded at finger deflections from 0 to 50 mm. Pull-out force was measured for individual established tomato transplants at MG-44 instrument-reported relative soil-moisture readings of 18% ($n = 5$) and 10% ($n = 7$) in the 0–100 mm layer. The force–deflection relationships were linear ($R^2 = 1.000$), and transplant pull-out force increased linearly with stem diameter ($R^2 = 0.991–0.994$). During field operation at a working width of 4.2 m, travel speed of 1.0–2.0 m s^{−1} and disc working depth of 1.5–5.0 cm, complete visible destruction was observed for weeds at the white-thread stage and no visible injury to established tomato plants was recorded. These field proportions were obtained in a non-randomized engineering verification and are therefore descriptive. Within the tested range, 73, 83 and 93 Shore A discs are provisionally recommended for crops with pull-out forces of at least 10, 15 and 25 N, respectively. An Euler–Bernoulli cantilever-beam analysis explains the observed linear response and identifies the contact conditions that favour finger sliding rather than crop displacement.

Key words: cantilever-beam model, finger weeder, pull-out force, polyurethane, Shore A hardness, tomato transplants.

INTRODUCTION

Mechanical inter-row and intra-row cultivation remains an important component of non-chemical weed management in transplanted vegetable crops, particularly where

hand weeding is labour-intensive and herbicide use is restricted. A wide range of passive and powered weeders has therefore been developed, from small-scale rotary machines to tractor-mounted finger and hoeing systems (Melander et al., 2005; van der Weide et al., 2008; Hegazy et al., 2014; Peruzzi et al., 2017; Abo-Habaga et al., 2018; Zawada et al., 2023; Trajkovski et al., 2024).

Effective weed removal directly within the crop row is nevertheless a major bottleneck because the working elements must disturb shallow-rooted weeds while passing close to the crop stem and root system. Elastic finger weeders can enlarge the treated area and break the surface crust, but their selectivity depends on operating settings, weed growth stage and crop anchorage (Raffaelli et al., 2011; Cirujeda et al., 2015; Asaf et al., 2023; Asaf et al., 2024; Parks et al., 2025).

The soil-tool interaction also changes with soil moisture, texture, strength, crusting and stone content. These factors influence penetration depth, soil displacement, energy demand, weed uprooting and the wear or accidental damage of working elements. Studies of spring-tine and rotary tools demonstrate that loading, depth, speed and cone index can markedly affect performance, while stony conditions may shorten tool life or require more compliant working elements (Zeng et al., 2021; Kumar et al., 2023; Gagliardi et al., 2024).

Recent systems increasingly combine mechanical tools with camera guidance, sensors and robotic actuation to reduce steering error. However, accurate navigation alone does not guarantee crop safety: the contact force generated by an elastic finger must remain below the mechanical resistance of the established crop while being sufficient to disturb the weed (Pérez-Ruíz et al., 2014; Machleb et al., 2020; Bulgakov et al., 2020a; Upadhyay et al., 2024). Tomato stem strength and failure behaviour also vary with stem geometry and tissue condition, reinforcing the need for crop-specific mechanical criteria (Bulgakov et al., 2021; Gao et al., 2024; Adamchuk et al., 2021).

Previous finger-weeder studies have mainly emphasized weed-control efficacy, operational settings or automated guidance, whereas fewer studies have linked the hardness of polymer fingers directly to measured crop pull-out resistance. Such a relationship could support safer setup of both conventional and automated intra-row cultivators and could provide a transparent basis for selecting interchangeable finger discs.

Accordingly, the aim of this study was to characterize the force-deflection response of polyurethane finger-star discs with three Shore A hardness values, compare their bending forces with the pull-out resistance of established tomato transplants, evaluate the working tool in a descriptive field verification, and interpret the interaction using a cantilever-beam model. The study was developed as an engineering proof of concept rather than as a replicated agronomic efficacy trial.

MATERIALS AND METHODS

Working tool and operating principle

The tested assembly comprised paired polyurethane finger-star discs mounted on spring-loaded units (Fig. 1). Three nominal material hardness values were examined: 73, 83 and 93 Shore A. Each polyurethane finger was 250 mm long and was inclined at 54 deg relative to the disc. The spring loading was intended to maintain shallow penetration over small changes in soil microrelief (Bulgakov et al., 2020b).

A two-stiffness finger concept was also considered: a more compliant tip zone would interact with the crop-row area, whereas a stiffer inner zone would disturb weeds farther from the crop stem. This concept has been submitted as a patent application and is presented here as a design direction rather than as a separately tested treatment.

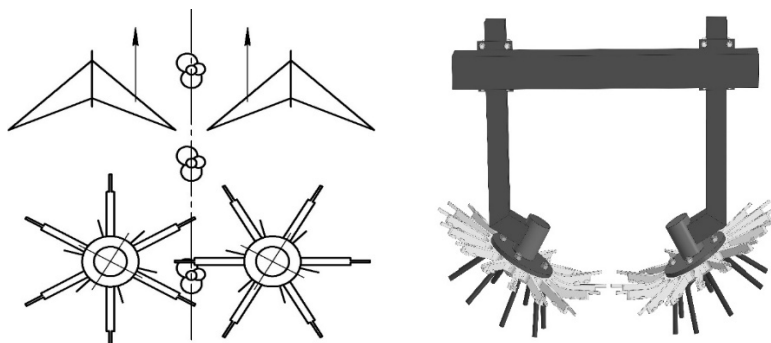


Figure 1. Scheme and 3D-model of rotary soil-working tool.

During forward travel, soil contact rotates the star discs and the elastic fingers enter the upper soil layer from both sides of the crop row. The fingers are intended to uproot or bury weakly anchored weeds, loosen the surface layer and disrupt a thin crust while deflecting around an established crop plant. The process is therefore governed by the balance between the force required to disturb a weed and the force that the crop and its root–soil system can withstand.

The device can be coupled with agricultural machinery ranging from a walk-behind tractor to a conventional tractor. Owing to the low mass of the modules and their ground-driven operating principle, high draft force is not required. The universal mounting permits installation on a profile frame with a side dimension of 60–100 mm; a cantilever bracket can also be used.

The investigation comprised three components: (i) laboratory characterization of finger force versus imposed deflection, (ii) an observational field measurement of tomato transplant pull-out force as a function of stem diameter at two soil-moisture readings, and (iii) a descriptive operational verification of the complete inter-row cultivator in established tomato rows (Fig. 2).



Figure 2. Operation of polyurethane finger-star discs in tomato rows.

Experimental scope and data structure

The laboratory calibration used three hardness treatments and six imposed deflection levels (0, 10, 20, 30, 40 and 50 mm). The retained laboratory record contained one force value for each hardness–deflection combination. The tomato pull-out dataset comprised five individual plants at an instrument reading of 18% and seven individual plants at 10%; each plant constituted one observational unit. The field weed-control component was a technical verification pass and was not established as a randomized replicated agronomic experiment. It had no untreated control, randomized plot allocation or plot-level replication, and the archived record did not contain plot dimensions or pre-treatment weed and crop densities. Consequently, ANOVA, treatment confidence intervals and plot-level error bars would not be statistically justified for the field percentages.

The tomato plants were established transplants with basal stem diameters of 3–10 mm and a maximum observed height of 50 cm. Their exact calendar age and planting depth were not retained in the experimental log; crop mechanical status is therefore reported using the measured stem diameter and pull-out force. The available soil record comprises only the MG-44 moisture readings in the 0–100 mm layer. Soil texture, bulk density, cone index, organic matter, stone content and crust strength were not measured, and the results are not presented as proof of applicability across different soils.

Laboratory force–deflection characterization

Each finger-star disc was fixed in the test arrangement shown in Fig. 3. A transverse load was applied to the free end of a finger with an AXIS FB 2k dynamometer, and finger deflection was set successively from 0 to 50 mm in 10-mm increments. Force readings were transferred to a personal computer. The same procedure was applied to discs with hardness values of 73, 83 and 93 Shore A.

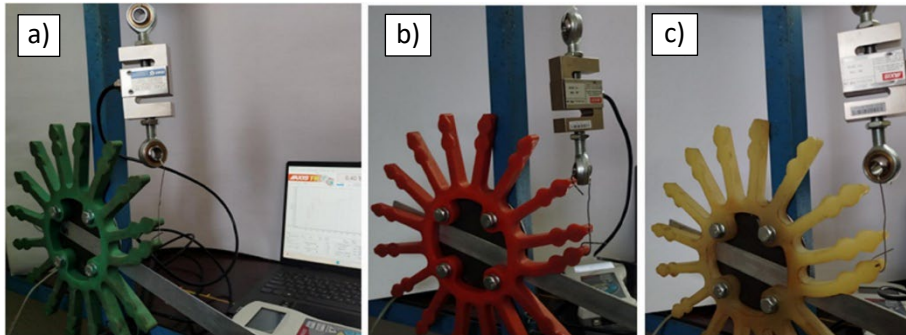


Figure 3. Laboratory testing of polyurethane finger-star discs with different Shore A hardness: a) 73 Shore A; b) 83 Shore A; c) 93 Shore A.

For each hardness, applied force was regressed on finger deflection by ordinary least squares with the intercept constrained to zero, which corresponds to zero load at zero deflection. The slope represents the effective transverse stiffness over the tested range. The coefficient of determination (R^2) and Pearson correlation coefficient (r) were calculated. The analysis is a calibration fit and does not estimate within-setting experimental variance.

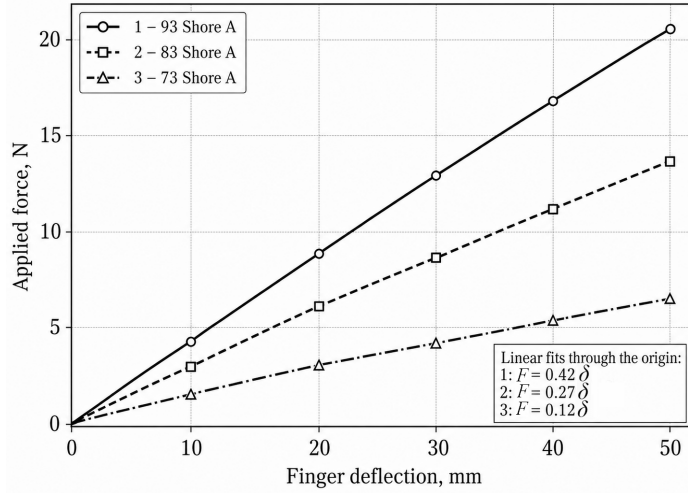


Figure 4. Measured force–deflection datapoints and linear fits for polyurethane fingers: 1 – 93 Shore A; 2 – 83 Shore A; 3 – 73 Shore A. F is applied force and δ is finger deflection.

Tomato transplant pull-out test

Soil moisture in the 0–100 mm layer was measured adjacent to the tested plants with an MG-44 soil moisture meter (Fig. 5, a). The values of 10% and 18% are readings on the instrument’s soil-specific relative-moisture calibration scale and are not gravimetric dry-basis water contents.

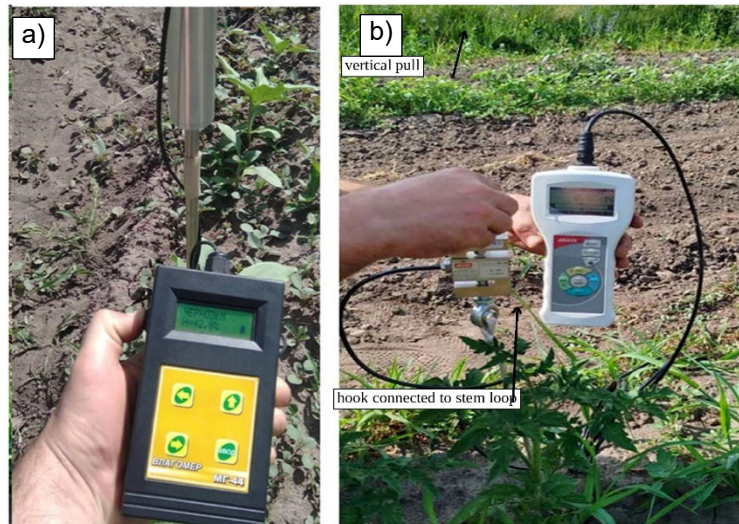


Figure 5. Field measurement procedure: a) MG-44 probe inserted in the 0–100 mm soil layer adjacent to a tomato plant; b) loading loop positioned around the stem base and connected to the AXIS FB 2k dynamometer, which was pulled vertically until complete uprooting. The peak displayed force was recorded.

Before pulling, basal stem diameter was recorded at the soil surface. A flexible loading loop was placed around the stem base and connected to the dynamometer; the load was increased approximately vertically until the plant was completely uprooted, and the peak force was recorded. Each plotted point in Fig. 6 represents one plant. Separate ordinary least-squares regressions were fitted for the two moisture strata, and R^2 and Pearson r were calculated. The moisture strata were observational rather than randomized treatments, so no factorial ANOVA was applied.

Descriptive field verification

The cultivator was operated with a working width of 4.2 m, a travel speed of 1.0–2.0 m s⁻¹ and a working depth of 1.5–5.0 cm for the polyurethane discs. The associated flat-cutting tools worked at 5.0–12.0 cm. Performance observations included visible weed destruction, surface-crust disruption and visible injury or uprooting of established tomato plants. Lambsquarters, pigweed and foxtail were assessed at the white-thread stage and, separately, at development up to three true leaves.

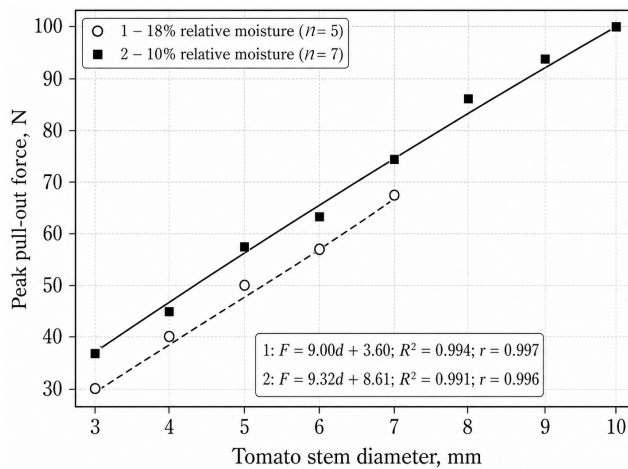


Figure 6. Tomato transplant peak pull-out force as a function of basal stem diameter: 1 – MG-44 relative-moisture reading of 18% ($n = 5$); 2 – reading of 10% ($n = 7$). Markers are individual plants; lines are least-squares regressions. Regression equations, R^2 and Pearson r are shown in the graph.

The reported values of 100% weed destruction at the white-thread stage, 100% visible crust disruption and 0% visible crop injury are observed proportions from the engineering verification, not means from independent randomized plots. For the larger weeds shown in Fig. 9, destruction varied by species and finger hardness.

Theory and modelling

A theoretical analysis was performed to describe the quasi-static interaction of a flexible finger with weeds and a crop plant. The finger was idealized as a homogeneous Euler–Bernoulli cantilever with constant bending stiffness EI , small transverse deflection and a concentrated external load. Dynamic impact, soil support

distributed along the finger, viscoelastic hysteresis and cyclic material fatigue were not included. During motion of the finger in the soil, weed sweeping or uprooting occurs provided that:

$$\frac{Q}{nF} \geq [\tau] \quad (1)$$

where Q – sweeping force acting on weeds, N; $[\tau]$ – allowable (critical) shear stress for a single weed plant; n – number of weeds swept simultaneously; F – cross-sectional area of a single weed stem. For crop plant contact, the same sweeping force is denoted as Q_1 .

From Eq. (1) we obtain:

$$Q \geq nF[\tau]. \quad (2)$$

If the weed stem diameter is d , then $F = \pi d^2 / 4$ and Eq. (2) becomes:

$$Q \geq n \frac{\pi d^2}{4} [\tau]. \quad (3)$$

If the finger undergoes a certain deformation from below, this does not significantly affect the weed sweeping process; the key requirement is that Eq. (3) is satisfied.

On the other hand, when the finger comes into contact with a crop plant, the sweeping force Q_1 must satisfy the condition:

$$Q_1 < F_1[\tau_1], \quad (4)$$

where F_1 – cross-sectional area of the crop stem; $[\tau_1]$ – allowable shear stress for the crop plant. If the crop stem diameter is d_1 , Eq. (4) becomes:

$$Q_1 < \frac{\pi d_1^2}{4} [\tau_1]. \quad (5)$$

The sweeping force Q_1 generates a bending moment that causes bending deformation of the flexible finger. To relate Q_1 to the bending moment, the Euler–Bernoulli equation for the elastic curve of a beam was used. The flexible finger was considered as a cantilever beam fixed at one end (Fig. 7).

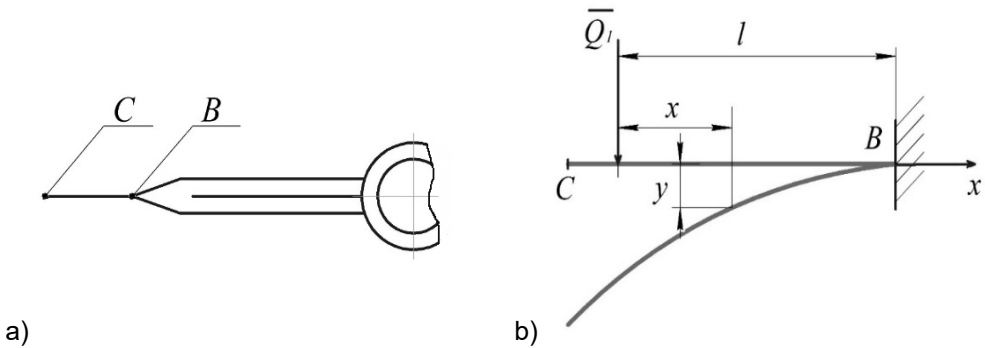


Figure 7. Bending deformation of a flexible finger during contact with a crop stem: a) structural scheme; b) design diagram. B is the fixed attachment at the disc hub, C is the free end of contact region, l is finger length, x is measured from C toward B , y is transverse deflection and Q_1 is the external crop-contact force.

Here and below, the crop-contact force is denoted Q_1 . The Euler-Bernoulli representation treats the finger as a cantilever fixed to the disc hub and is used to connect that force with transverse deflection.

In the notation of Fig. 7, a is the generic crop-contact point referred to in the derivation, B is the fixed end at the disc hub ($x = l$), and C is the free end ($x = 0$).

In the general case, consider the contact of the flexible finger with the crop stem at point A . At this point, the external load Q_1 acts on the finger from the plant. The bending moment at a cross-section located at a distance x from the free end is:

$$M(x) = -Q_1 x. \quad (6)$$

The differential equation of the elastic curve is:

$$\frac{d^2 y}{dx^2} = \frac{M(x)}{EI}. \quad (7)$$

where EI is the beam bending stiffness (E – Young's modulus, I – second moment of area); y is the deflection at section x .

Substituting Eq. (6) into Eq. (7) yields:

$$\frac{d^2 y}{dx^2} = -\frac{Q_1 x}{EI}. \quad (8)$$

The boundary conditions for Eq. (8) are:

$$x = l : y = 0, \theta = \frac{dy}{dx} = 0. \quad (9)$$

where θ is the rotation angle of the beam cross-section and l is the beam length.

After the first integration of Eq. (8) we obtain:

$$\frac{dy}{dx} = -\frac{Q_1 x^2}{2EI} + C_1. \quad (10)$$

After the second integration of Eq. (8) we obtain:

$$y(x) = -\frac{Q_1 x^3}{6EI} + C_1 x + C_2, \quad (11)$$

Using the boundary conditions (9), the integration constants are:

$$C_1 = \frac{Q_1 l^2}{2EI}, \quad C_2 = -\frac{Q_1 l^3}{3EI} \quad (12)$$

Substituting C_1 and C_2 into Eq. (11) yields:

$$y(x) = -\frac{Q_1 x^3}{6EI} + \frac{Q_1 l^2 x}{2EI} - \frac{Q_1 l^3}{3EI}. \quad (13)$$

The most favourable conditions for avoiding crop damage occur when the flexible finger contacts the plant at the free end. In this case, the deflection is maximal and the bending moment is zero. From Eq. (13), $y(0) = -\frac{Q_1 l^3}{3EI}$ and $M(0) = 0$.

The least favourable conditions occur when contact takes place near the fixed end (point B). In this case, $y(l) = 0$ and the bending moment reaches its maximum magnitude.

Thus, contact close to C is favourable because the finger can develop a large displacement and slide around the stem, whereas contact close to B constrains displacement and increases the bending moment: $M(l) = M_{\max} = -Q_1 \cdot l$

Fig. 8 illustrates the technological scheme of operation of polyurethane rotary finger-star discs.



Figure 8. Technological scheme of operation of polyurethane rotary finger-star discs.

Therefore, the farther the contact point is from the fixed end, the greater the available finger deflection and the more readily the bent finger can slide around the stem. Contact near the hub produces a smaller displacement and a larger moment, increasing the probability of stem abrasion, crop displacement or finger overload.

Model validation was assessed at the response-form level. For a cantilever subjected to a free-end load, Eq. (13) predicts a linear relationship between force and deflection when EI and l are constant. The calibration data in Fig. 4 followed this prediction ($R^2 = 1.000$ for all three hardness grades). This agreement supports the assumed linear response over 0–50 mm, but it is not a complete parameter-level validation because Young's modulus, cross-sectional second moment of area, dynamic contact duration and distributed soil resistance were not independently measured.

RESULTS AND DISCUSSION

The effective force–deflection slopes were 0.120, 0.270 and 0.420 N mm⁻¹ for 73, 83 and 93 Shore A, respectively (Fig. 4). At 50 mm deflection, the corresponding forces were approximately 6.0, 13.5 and 21.0 N. Thus, increasing Shore A hardness increased the transverse force transferred to a contacted plant. All calibration relationships were linear over the tested range ($R^2 = 1.000$; $r = 1.000$).

These trends are consistent with the cantilever model: lower effective bending stiffness permits greater deflection at a given contact force, whereas a stiffer finger transmits a larger load. Surface smoothness remains an additional safety factor because a lower finger–stem friction coefficient favours sliding and reduces local abrasion. The proposed two-stiffness design should therefore be evaluated not only for stiffness but also for surface friction and cyclic durability.

A crop stem can likewise be idealized as a cantilever for a first mechanical interpretation, but the living plant and the root-soil system are heterogeneous, tapered and moisture-dependent. Accordingly, the measured whole-plant pull-out force was used as the practical safety comparator rather than relying solely on a theoretical stem stiffness.

The pull-out force increased strongly with basal stem diameter. At the 18% relative-moisture reading, the fitted relationship was $F = 9.00d + 3.60$ ($R^2 = 0.994$; $r = 0.997$; $n = 5$), whereas at 10% it was $F = 9.32d + 8.61$ ($R^2 = 0.991$; $r = 0.996$; $n = 7$), where F is force in N and d is diameter in mm. The observed range was approximately 30–100 N, which exceeded the maximum 50-mm bending force of each tested finger.

The higher fitted force at the drier 10% reading is mechanically plausible because soil moisture can alter root–soil adhesion and soil failure around the root system. However, the present moisture strata were observational and the soil texture and strength were not characterized; therefore, the difference should not be interpreted as a causal moisture effect.

For practical screening, the measured maximum bending forces were rounded upward to provisional minimum crop pull-out thresholds of 10, 15 and 25 N for 73, 83 and 93 Shore A discs, respectively. These thresholds provide only a modest static margin and apply to established plants within the tested geometry and operating range.

Field performance and practical interpretation

During the descriptive field pass, all visible weeds at the white-thread stage were destroyed, the observed thin surface crust was disrupted and no visible injury or uprooting of established tomato plants was recorded. These outcomes represent the tested pass only. They must not be extrapolated to weeds at later stages: Fig. 9 shows that destruction of lambsquarters, pigweed and foxtail at up to three true leaves varied substantially with species and hardness, approximately from 5% to 90%.

The descriptive percentage of destroyed weeds at development up to three true leaves is shown in Fig. 9.

The combined results support the engineering rationale for an improved finger with a compliant low-friction tip and a stiffer inner zone. A spring-loaded mounting can stabilize shallow

penetration over minor microrelief, but it cannot compensate for large changes in soil strength, stones, dense crusts or incorrect guidance. Tool hardness, contact location, finger surface and crop anchorage should therefore be considered together.

The complete removal observed for white-thread weeds agrees with the established finding that very young weeds are especially susceptible to shallow uprooting or burial (Melander et al., 2005). Published field studies generally report wider and lower efficacy ranges when weeds are larger or conditions are heterogeneous. Finger-weeder

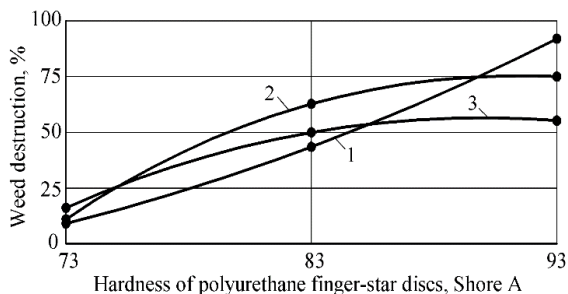


Figure 9. Observed weed destruction at development up to three true leaves as a function of polyurethane finger hardness: 1 – lambsquarters; 2 – pigweed; 3 – foxtail.

performance has been related to weed uprooting force and morphology (Asaf et al., 2023; Asaf et al., 2024), and controlled tests show important effects of finger angle, spacing and speed on both efficacy and selectivity (Parks et al., 2025). The variable values in Fig. 9 are therefore more representative of the expected response once weeds have developed true leaves.

Soil condition is a central limitation. Tomato studies have shown that crusting and timing can make mechanical intra-row control uneven (Raffaelli et al., 2011; Cirujeda et al., 2015). More generally, spring loading, working depth, speed and soil cone index alter soil displacement and energy demand (Zeng et al., 2021; Kumar et al., 2023). Stony soils can also accelerate damage to rigid or rotating tools and may favour more compliant designs (Gagliardi et al., 2024). These findings explain why the present single-site observations cannot establish performance or finger lifespan across soil textures.

Crop safety remains a key criterion for intra-row cultivation. Intelligent guidance reduces steering error (Pérez-Ruíz et al., 2014; Melander et al., 2015; Machleb et al., 2020), while recent reviews emphasize the need for robust modular tools in robotic weed management (Upadhyay et al., 2024). The present hardness–pull-out comparison complements navigation by providing a mechanical screening rule. Nevertheless, tomato tissue strength depends on stem geometry and tissue condition (Gao et al., 2024), so a safe setting should be verified for the crop stage and local soil before routine operation.

Limitations and future research

The principal limitations are the absence of a randomized replicated field design and untreated control; unavailable plot size, initial weed and plant densities and replicate-level weed counts; one field site; unrecorded soil texture, bulk density, cone index, stone content and crust strength; instrument-relative rather than standardized gravimetric moisture values; only two moisture readings; established transplants of unrecorded calendar age and planting depth; a travel-speed range limited to 1.0–2.0 m s⁻¹; and no direct measurement of finger wear, fatigue life, Young's modulus, contact dynamics or crop-stem abrasion. The 100% weed destruction and 0% crop injury values must consequently be interpreted as descriptive observations under favourable early-stage conditions.

Future work should use a randomized factorial design across contrasting soil textures, moisture and cone-index levels, crust strengths and stone contents; include untreated controls, replicated plots, initial and final weed densities, crop injury ratings and confidence intervals; test several transplant ages, planting depths, crop species, weed stages and wider speed ranges; and quantify polyurethane mass loss, dimensional change, stiffness drift and failure after defined operating cycles or hectares. Independent measurements of *E* and *I*, high-speed contact forces and distributed soil resistance are also needed for parameter-level model validation and for adaptive robotic control.

CONCLUSIONS

1. Polyurethane finger-star discs provided gentle shallow soil disturbance around established tomato plants and completely removed visible white-thread weeds during the descriptive verification; efficacy for weeds with true leaves was lower and species- and hardness-dependent.

2. Force–deflection relationships for 73, 83 and 93 Shore A fingers were linear over 0–50 mm ($R^2 = 1.000$). Tomato pull-out force increased with stem diameter at both instrument-relative moisture readings ($R^2 = 0.991$ – 0.994) and exceeded the measured finger-bending forces.

3. Within the tested geometry and operating range, provisional minimum crop pull-out thresholds of 10, 15 and 25 N are proposed for 73, 83 and 93 Shore A discs, respectively. These are engineering screening values rather than universal crop-safety limits.

4. The cantilever-beam model correctly predicts the observed linear response and indicates that contact near the free finger end is mechanically safer than contact near the hub. General validation across soils and crop stages, together with replicated efficacy and durability trials, remains necessary.

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