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# Development and Evaluation of a Prototype Precision Harvesting Unit for Medicinal Plants – Tested on *Hyssopus officinalis* L.

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**ABSTRACT**

Precision management of medicinal plant production using mechanical systems, processors, and sensors increases productivity, reduces waste, and manages production processes. This research developed a precision harvesting unit equipped with an automatic height adjustment system for utilization in harvesting machines to harvest Hyssop at an optimal height. The unit after development consisted of a power transmission system (converting rotational motion into reciprocating motion), a harvesting platform (cutter-bar, reel, and conveyor), and a system to control the vertical movement of the head. An ultrasonic sensor was employed to detect the highest part of the plant for control purposes. A central control board and a driver generated the control signal, with a stepper motor as the actuator. We measured harvesting-related variables, including dry matter, essential oil content and yield, leaf-to-stem ratio, and indices related to conservation agriculture to evaluate the developed precision harvesting unit. Results showed that the unit increased the purity of the harvested plant raw material compared to the manual harvesting of Hyssop, a key to extracting more of the target substances, such as essential oil. The steady-state error of the control system measured 2% in adjusting the cutter-bar height for the optimal height of harvesting Hyssop (T15) in elevation and descension modes.

## Introduction

Given the benefits of active compounds in medicinal and aromatic plants, interest in drugs and cosmetics with plant origins has steadily risen over the past decades. The value of global trade in medicinal plants averaged $62 billion in 2017 (Alamgir, 2017). In the production and exploitation of medicinal plants, harvesting is one of the most sensitive and, at the same time, the costliest steps (Kaminski and Zoerb, 1965; Souček and Blažej, 2012). New harvesting technologies are needed to improve and increase the quality of raw materials obtained from these plants (Ebadi et al., 2017; Ahangarnezhad et al., 2019). Considering the presence of different plants, developing medicinal plant harvesting machines is a must. Since many farmers avoid cultivating such plants because of problematic harvesting, developing new technologies is necessary (Beier and Ehlert, 2014b; Lelei et al., 2020). Precision harvesting is a subset of precision agriculture in that the plant is harvested

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at its optimal height (not at the soil surface). As a result, by not harvesting all organs, the plant matures and grows back more quickly, enabling more harvests through the growth season (Mighri et al., 2009). The pharmaceutical sector requires plant components that are of the highest quality. Thus, plants are usually classified based on their organs (i.e., roots, leaves, or flowers) (Beier and Ehlert, 2014a). These organs should not have sustained any damage and must be separated from unwanted plant parts. Many factories ensure this by choosing and recommending manual harvesting to increase precision at harvest and produce less waste (Ghareeb et al., 2022; Franke and Schilcher, 2005; Ghezel et al., 2022). In terms of more accumulation of active components in branches, reducing the quality of raw material with the presence of stems, and the importance of leaving non-commercial parts on the farm to help conservation agriculture, the importance of harvesting plants at a desired height can be a solution (Saebi et al., 2021; Thierfelder et al., 2013). Most research on harvesting machines considered the type of harvesting heads, reduced cutting of additional stems, transfer, storage, and decreased harvesting time compared to manual harvesting (Hegazy et al., 2011; Stolarski et al., 2022; Ebadi et al., 2017; Tabatabaei and Borgheei, 2006; Massah et al., 2021; Souček and Blažej, 2012; Rezahosseini et al., 2019; Bazyar et al., 2019). A group of researchers, such as Mesas-Carrascosa et al. (2015), suggested new mechanisms and machines for harvesting. Bluecher 02/03 used two cylinders on standing stems for harvest.

However, the machine's performance diminished in response to the wind by bending. By placing the harvesting head in the upper part of the chassis, the Hemocut 3000/4500 could harvest plants at 60-70 cm height, although needing high power. The highest yield per hectare belonged to Clipper 4.3 MMH, harvesting products with three cutter-bars at different heights, followed by quick drying (Pari et al., 2015; Manian et al., 2021). In another type of research, controlling the harvesting head was noticed to prevent collisions with the ground (Gharakhani et al., 2017; Zhao et al., 2022). Some other researchers considered using an ultrasonic sensor at the beginning of the machine’s movement to adjust the harvesting head. However, it needed multiple adjustments along with the driver's harvest route (Ehlert and Beier, 2014).

The cultivated farm area (square meters) is a crucial factor in realizing sustainable agriculture and justifying the purchase of a unique harvesting machine (Ivanović et al., 2014). However, fewer capacity machines reportedly had applicability in some countries due to smaller farms. In no research so far have researchers taken a closed-loop system that provided automatic and continuous harvesting head height adjustment without stopping the machine. So, the main aim of this research was to develop a closed-loop control system that provides automated, ongoing harvesting head height adjustment and functional evaluation in practical conditions. The harvesting height should be the first loop of the food chain to produce high-quality raw material that meets the needs of the food/pharmaceutical industry. *Hyssopus officinalis* L. was used to test the unit. Hyssop's precision harvesting can achieve purer active compounds from Hyssop.

## Materials and Methods

The harvesting unit envisioned in the project included mechanical and electronic systems explained herein. The mechanical part consists of the power transmission system, converting rotational motion into reciprocating motion, and a mechanism for cutter-bar height adjustment. The harvesting unit's electronic part has an ultrasonic sensor, sensor signal acquisition program, data analysis, and a command signal transmission to the actuator (stepper motor). A schematic illustration of the harvesting unit appears in Figure 1 (SOLIDWORKS version 2016, Dassault Systems Corporation, Waltham, Massachusetts).

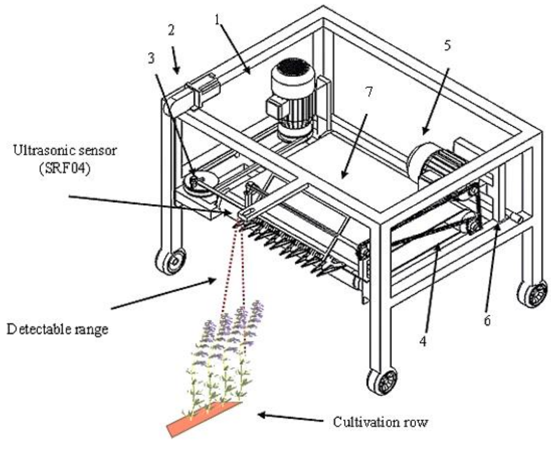


**Fig. 1.** Schematic illustration of a precision harvesting unit and identification of a plant's highest part by an ultrasonic sensor (1. cutter-bar’s electromotor, 2. stepper motor and gearbox, 3. rotational motion into a reciprocating motion mechanism, 4. conveyor and reel drive train, 5. conveyor’s electromotor (0.5 hp), 6. hinged part, 7. conveyor assembly).

### *Chassis of the harvesting unit*

In the design of a precision harvesting unit, the chassis must support other parts and the distance of cultivation rows (here 50 cm). Thus, 90×65×65 cm was deemed suitable for the chassis dimensions.

### *Cutting mechanism*

Two mechanisms, namely, cutter-bar and grass cutter, were studied when selecting the cutting mechanism. Due to chassis placement space restrictions and the need for harvesting at a high height, we eliminated the grass cutter method from consideration while employing a tiller cutter-bar as the cutting device. After adequate calculations, an electromotor served as a power source for the cutter-bar. According to Fig. 2, the pulley, belt, and connector cooperated to convert rotational motion into reciprocating motion.
Considering linear motion constraints, the diameters of the first and second pulleys were selected, 10 and 4 cm, respectively (Fig. 2). A suitable speed of the cutter-bar (back-and-forth-moving) was about 3 m $s^{-1}$ in harvesting with a cutter-bar mechanism (Klenin et al., 1985).

**Fig. 2.** Precision harvesting in prototype testing.

A height adjustment system was developed to provide vertical head movement. For this purpose, a stepper motor was installed to supply the adequate steps. To provide the required torque, the stepper motor was connected to a gearbox with a torque ratio of 1:8. The driver was programmed in CodeVisionAVR Software, version 3.12 (Atmel Corporation, San Jose, California, USA) (Table 1). A cable drum was attached to the gearbox output shaft, and connected to the cutter-bar (Fig. 3).

**Table 1.** Electronic components and their specifications.

| Electronic equipment | Characteristic |
|---|---|
| Electromotor | 3-phase 1.5 kW (2 hp)/ 380 v |
| Stepper motor | Sanyo 103-810-14 / 1.8 °/ 275 N. cm Torque |
| Driver | MOON SR8-Plus |
| Ultrasonic sensor (SRF04) | Range: 2 cm-4 m/ Beam Width: Up to 15 degrees |
| Control board | Arduino UNO (Arduino SRL, Strambino, Italy) |

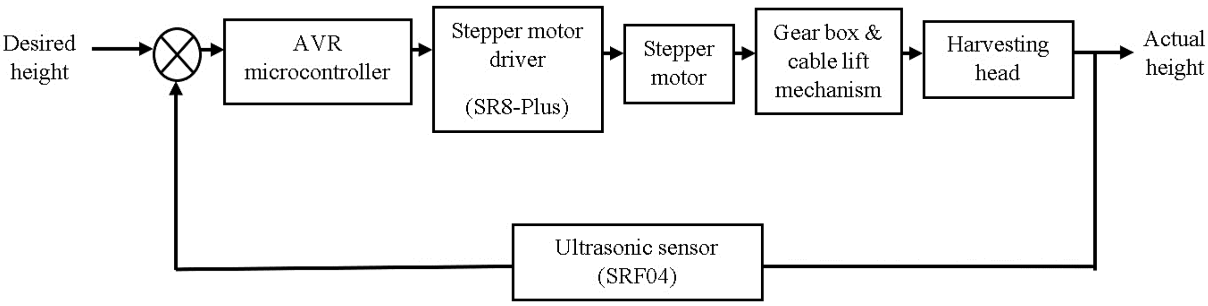


**Fig. 3.** Block diagram of the harvesting head height control system.

### *Measurement mechanism and distance control*

An ultrasonic sensor was placed in the upper part of the chassis to detect a plant's highest part (Fig. 1). The measured distance was compared to the set-point (cutting heights) written in the software and a proper command was sent to the actuator. An Arduino UNO board generated the control signal after amplifying the signal by the driver. Schematics of the electronic setup and specifications are shown in Figure 4 and Table 1, respectively.

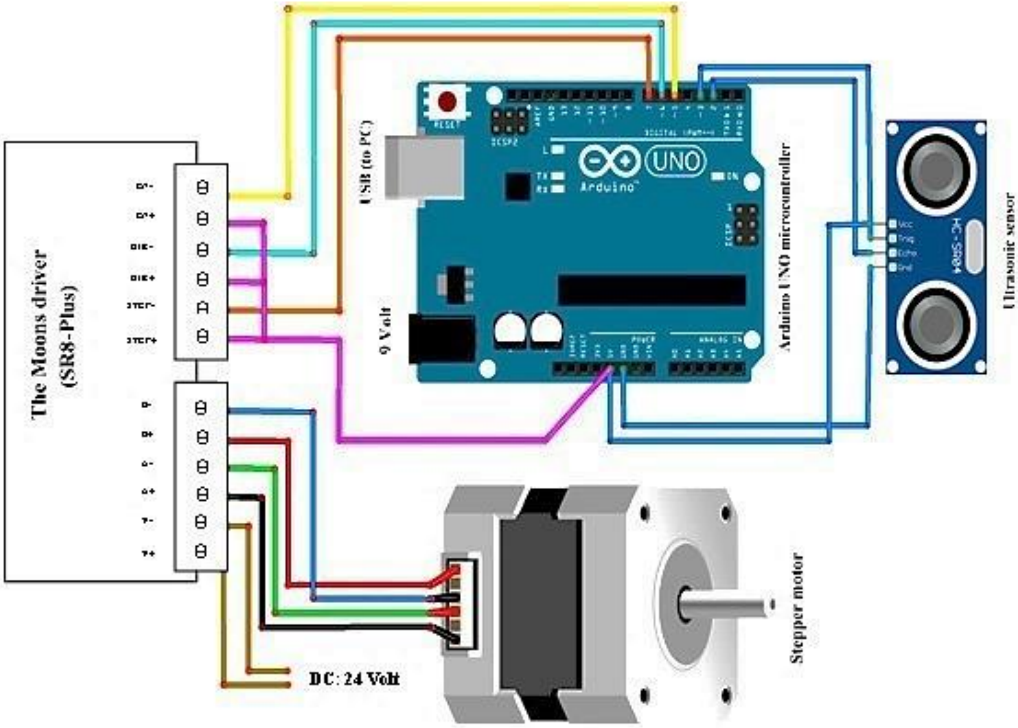


**Fig. 4.** Schematics of the electronic setup.

An ultrasonic sensor provided a suitable measurement range for this project (10 cm). Since the sensor should detect the highest part of the plant, its field of view should detect one cultivation row (the cone angle is approximately 30 degrees). Major components of the harvesting unit (Fig. 1) consisted of 1. a cutter-bar electromotor, 2. a stepper motor and gearbox, 3. rotational motion into a reciprocating motion mechanism, 4. a conveyor and reel drive train, 5. a conveyor's electromotor (0.5 hp), 6. hinged part, 7. conveyor assembly.

### *Investigating the precision harvesting method and its effects*

After assembling, the harvesting unit performance in a Hyssop farm was evaluated (Fig. 2). Dry matter, essential oil content/yield, and leaf-to-stem ratio were measurable at harvest in various height set points. The main reason for selecting these variables was to enhance industrially valuable substances to achieve high purity and quality, thus increasing the percentage of essential oil per unit weight of harvested plant. Data analysis involved using an LSD test ($P \leq 0.05$) via SPSS software, version 22 (IBM Corporation, Armonk, New York, USA). The experiment appeared in a randomized complete block design (RCB) with three replications. Experimental treatments included four harvest heights, i.e., 15, 25, 35, and 45 cm (measured from the highest part of the plant: T15, T25, T35, and T45) and residual stalk heights (non-harvested parts) at 15, 25, and 35 cm (15R, R25 and R35) (Fig. 5).

## Results

### *Technical evaluation of the harvesting unit*

The initial launch of the harvesting unit occurred, followed by studying the control system response to step inputs (cutting heights). Regarding the weight of the harvesting head, the control system was separately examined in elevation (raising) and descension (lowering) modes. Response characteristics included the following as indices: rise time, peak time, settling time, maximum overshoot, response-curve initial slope, and steady-state error (Fig. 6) for each height ((elevation mode: +15, +25, +35) and (descension mode: -15, -25, and -35)) (Tables 2 and 3).

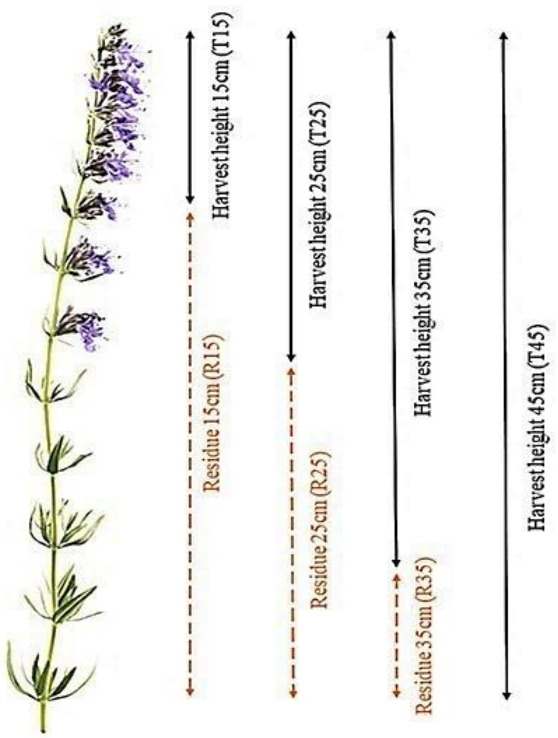


**Fig. 5.** Height labelling indicating harvested vs. residual stalk portions.

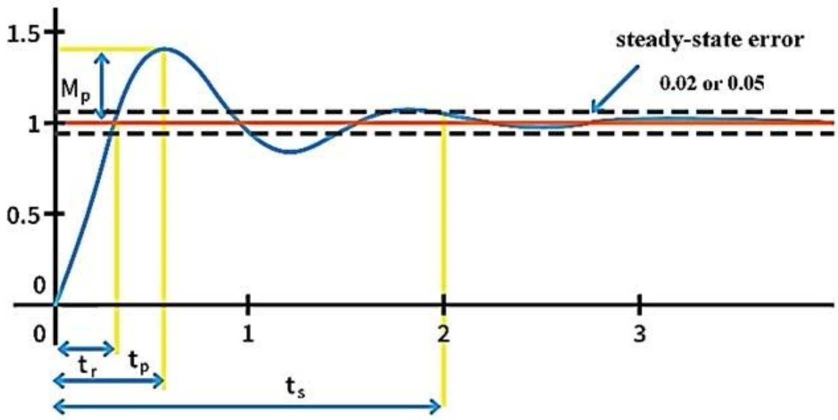


**Fig. 6.** Control system response characteristics.
($Mp$: maximum overshoot, $tr$: rise time, $tp$: peak time, $ts$: settling time)

**Table 2.** Control system transient response characteristics (elevation mode).

| Variables | +15 cm | +25 cm | +35 cm |
|---|---|---|---|
| Rise time $t_r$ (S) | 12.73 | 16.42 | 18.21 |
| Peak time $t_p$ (S) | - | - | - |
| Settling time $t_s$ (S) | 22.22 | 32.65 | 43.71 |
| Maximum overshoot $M_p$(%) | - | - | - |
| Initial slope | 0.3245x | 0.4603x | 0.5987x |
| Steady-state error $e_{ss}$ (%) | 2 | 2 | 5 |

**Table 3.** Control system transient response characteristics (descension mode).

| Variables | -15 cm | -25 cm | -35 cm |
|---|---|---|---|
| Rise time $t_r$ (S) | 3.71 | 6.62 | 9.88 |
| Peak time $t_p$ (S) | 4.57 | 13.11 | 19.81 |
| Settling time $t_s$ (S) | 7.57 | 17.32 | 25.95 |
| Maximum overshoot $M_p$(%) | 8 | 10.05 | 11.43 |
| Initial slope | 0.4510x | 0.6595x | 0.7522x |
| Steady-state error $e_{ss}$ (%) | 2 | 5 | 5 |

Evaluations of the harvesting head in the elevation mode (Table 2) showed that since no overshoot occurred, the system response dampened while achieving the desired heights of +15, +25, and +35 cm. Examining the rise time for this mode showed that it took 12.73, 16.42, and 18.21 seconds to reach 100% of the final value for +15, +25, and +35 cm set points, respectively. Regarding a step input, the settling time was 22.22, 32.65, and 43.71 seconds for +15, +25, and +35, respectively. The steady-state error was 1.3, 0.9, and 1.6 cm for -15, -25, and -35 cm set points, respectively. These results indicated that the final amounts of these steps were in steady-state error bands of 2%, 2%, and 5%, respectively.
According to an analysis of the rise time in the descension mode (Table 3), the response times for set points at -15, -25, and -35 cm were 3.71, 6.62, and 9.88 seconds, respectively. In this mode, the harvesting head covered the distance to the final value within a short period with less time to reach lower height set points. The peak time in this mode, which shows the existence of an underdamped system, was 4.57, 11.1, and 19.81 seconds for -15, -25, and -35 cm set points, respectively. The maximum overshoot was 8%, 10.05%, and 11.43% for -15, -25 and -35 cm set points, respectively. In other words, the lower height set points resulted in lower overshoot. This observation was expected due to the force of gravity acting on the harvesting head, affecting the gearbox shaft output. Values of the settling time in descension mode were 7.57, 17.32, and 25.95 seconds for -15, -25, and -35 cm set points, respectively. The steady-state error was 13.8, 24.5, and 34 cm for -15, -25, and -35 cm set points, respectively, and showed the final values stayed within 2%, 5%, and 5% steady-state error bands, respectively.

### *Dry matter, essential oil content, and leaf-to-stem ratio*
The amount of dry matter, essential oil content/yield, and leaf-to-stem ratio in harvesting from different heights appear in Table 4. Attempting to make harvests at a lower height resulted in a 69.93% reduction in essential oil output. Therefore, harvesting the higher plant parts rather than the lower regions was crucial for boosting essential oil contents (36% increase). Based on the results, the highest leaf-to-stem ratio appeared in the stems ($2.7 \pm 0.29$). In areas closest to the ground, with a notable reduction in leaf density and increased stem diameter, a 63.71% decrease in this ratio referred to the stem's absence in non-harvestable parts.

## Discussion
### *Performance of the harvesting unit*
Harvesting height is a determining factor in the overall harvest performance. With a lower harvesting height, the probability of entering external objects into the harvesting machine increases (Coleman and Northup, 1979; Žitňák et al., 2015). In previous research carried out by Kaminski and Zoerb (1965), this amount was considered 7.5-10 cm above the soil surface. Some researchers indicated that harvesting height is a function of machine performance and suggested that it be from 0.25 to 0.33 of plant height (Pask, 1975).
In feedback control systems (closed-loop), the output cannot immediately follow the sudden input changes due to unavoidable inertia and tolerance, so a transient state emerges in system performance. A comparison of the steady-state response with the input indicates the system's accuracy (Ogata, 1999; Sayyar-Rodsari, 2011; Miller and Lundeberg, 2010). The system has a steady error if the steady-state response differs from the input. It is necessary to have a criterion for comparing and evaluating different systems to analyze control systems. This criterion can be the output of those systems to a specific input signal (Prisco et al., 2010; Perez, 2019; Krishnamurthy and Khorrami, 2007; Yazdani et al., 2018). In this study, the input signal was the stepper-motor output shaft rotation to provide the desired heights of 15, 25, and 35 cm in elevation and descension modes that reached these heights with an accuracy of 2% and 5% (Tables 2 and 3).

**Table 4.** Effect of the harvest height on dry matter, essential oil content/yield, and leaf-to-stem ratio.

| Treatments (cm) | Dry matter (g m$^{-2}$) | Essential oil content (%) | Essential oil yield (g m$^{-2}$) | Fresh leaf-to-stem ratio |
|---|---|---|---|---|
| T15 | 213.72±15.32$^{c}$ | 1.02±0.01$^{a}$ | 2.17±0.13$^{b}$ | 2.7±0.29$^{a}$ |
| T25 | 465.48±145.87$^{bc}$ | 0.93±0.02$^{b}$ | 4.38±1.44$^{ab}$ | 2.01±0.32$^{b}$ |
| T35 | 607.53±61.74$^{ab}$ | 0.85±0.02$^{c}$ | 5.16±0.63$^{a}$ | 1.39±0.15$^{c}$ |
| T45 | 757.52±63.5$^{a}$ | 0.75±0.01$^{d}$ | 5.7±0.57$^{a}$ | 0.98±0.19$^{d}$ |
| LSD | 260.66 | 0.04 | 2.43 | 1.09 |
| R15 | 531.62±37.09$^{a}$ | 0.62±0.02$^{a}$ | 3.27±0.2$^{a}$ | 1.28±0.19$^{a}$ |
| R25 | 345.49±57.21$^{b}$ | 0.53±0.01$^{b}$ | 1.83±0.32$^{b}$ | 1.13±0.16$^{b}$ |
| R35 | 186.98±17.57$^{c}$ | 0.42±0.02$^{c}$ | 0.78±0.05$^{c}$ | 0.96±0.02$^{c}$ |
| LSD | 142.76 | 0.08 | 0.93 | 0.26 |

T15, T25, T35, and T45 were harvest heights from the highest part of the plant while 15R, R25 and R35 were residual stalks of the 15, 25, and 35 cm heights. LSD: least significant difference.

Considering the commercial importance of leaf and stem, the height of medicinal plants where the cut appears is vital for the food/pharmaceutical industry, first for their youth and second for fewer woody stems. According to González-Buesa and Salvador (2019), due to the importance of the quality of the harvested crop, as opposed to quantity, using suitable means of control, such as a closed-loop control system, simplicity, adaptability, and low cost, can be beneficial. The present idea and parameters showed that using these systems with the appropriate steady-state error of the harvesting unit's performance was suitable in elevation and descension modes (Tables 2 and 3).

### *Overall view on raw materials and benefits of precision harvesting for conservation agriculture*

By increasing harvesting height, the dry matter increased by 71.79% due to the natural increase in plant biomass, consistent with results reported in the literature (Khazaie et al., 2008). These results showed that essential oil yields are directly related to dry matter (Moradi et al., 2021). In addition, the results revealed a negative correlation between dry matter and essential oil content, confirming previous findings by Misra and Sharma (1991). Moreover, regarding the leaf-to-stem ratio, plant leaves have more protein and fewer fibers than stems, thus affecting product quality (Ball et al., 2001). On the other hand, this ratio is more vital in plants with larger stem diameters near the ground surface (Kochaki and Sabet-Teimori, 2011). In general, high-quality raw materials are achievable through knowledge of the potential of different plant parts for arriving at an optimum cutting height.

In addition to direct effects on the quality of the resulting raw materials, precision harvesting is also beneficial for conservation agriculture. Conservation agriculture is an approach based on minimum soil disturbance, maintaining crop residue, reducing water consumption, and controlling soil erosion on the farm, which helps increase productivity as well as benefit the environment (Thierfelder et al., 2013; Wijitkosum and Jiwnok, 2019; Gatahi, 2020). In the present study, harvesting from T15 (desirable height for food/pharmaceutical industries) compared to T45 left 71.78% of stalks as residue, meaning that 74.75% of the nitrogen accumulated in the aerial part of plant residues on the farm. Several studies have noted the importance of leaving post-harvest residues in the soil, as summarized in Table 5.

## Conclusion

A precision harvesting unit equipped with a power transmission system appeared harmonious with the reel, and the conveyor was developed and tested. The unit uses an automatic control system to adjust the harvesting height in response to spatial variation in plant height. Based on laboratory tests of the unit, comparing the steady-state response with step inputs demonstrated that the feedback control system adjusted the harvesting unit with an accuracy of 2% in elevation and descension modes for the optimal cutting height (T15). The precision harvester unit was successful in tests after development on Hyssop crops at various heights.

The evaluation of harvesting-related variables (dry matter, essential oil content/yield, and leaf-to-stem ratio) showed differences in the degree of purity and active components at various heights of Hyssop. Moving from T15 to T45 of the harvesting height resulted in a 26.7% decrease in the obtained essential oil. The results indicated that 71.78% of residual stalks remained on the farm, notable for conservation agriculture. The know-how in developing and testing this prototype can be valuable in bringing on industrial-scale precision harvesting machines for medicinal plants.

**Table 5.** Conservation agriculture as affected by precision harvesting.

| Research topic | Variables examined | Results | Reference |
|---|---|---|---|
| Corn yield in two tillage and no-tillage conditions | ● Tillage<br>● Maintain the residues<br>● Consumption of fertilizer | ● Fertilization was the strongest factor affecting yield in both tillage and no-tillage systems<br>● Maintaining residues of harvesting increased total yield in no-tillage system<br>● No-tillage system-residues, compared to tillage, caused a 50% reduction in total yield | (Thierfelder et al., 2013; Turmel et al., 2015) |
| Sustainable harvesting products | ● Harvesting from different parts of the plant<br>● Harvesting branch<br>● Harvest intensity | ● Sustaining animal species by maintaining residues on the farm<br>● Re-assignment of plant storage resources in perennial plant cultivation and accelerating growth by not harvesting the whole plant<br>● Not harvesting the whole plant by maintaining the germination parts<br>● Maintaining soil nutrients and reducing its erosion by keeping residues on the farm | (Ticktin and Shackleton, 2011) |
| Excessive harvesting and limited knowledge of farmers | ● Distribution of plant biomass<br>● Farmers' income | ● Extreme reduction of wood available<br>● Destruction of 57% of | (Van Andel et al., 2015; Osman, 2011) |

| | | | |
|---|---|---|---|
| | | the natural habitat of plants<br>● Reducing farmers' revenue<br>● Reducing organic cultivation<br>● Use of chemical products against organic ones | |
| Relationship of conservation Agriculture with Climate Change | ● Water permeation rate<br>● Soil moisture | ● Increased water permeation rates up to 5 times compared to non-conservation farms<br>● High levels of soil moisture in the fields under conservation practice | (Thierfelder and Wall, 2010) |
| Relationship between managing the harvest height and conservation agriculture on the amount of fertilization and remaining elements in the plant | ● Amount of accumulated elements in different heights of the plant<br>● Amount and frequency of fertilization<br>● Fertility of the soil | ● Positive effect of harvesting height on reducing the amount of heavy elements in the harvested crop<br>● Increase the purity of the ultimate active compounds<br>● Fixing 30% nitrogen and 50% potassium into the soil<br>● Stabilization of soil nitrogen | (Thierfelder et al., 2013; Raza et al., 2020; Saebi et al., 2021) |
| Sustainable agriculture | ● Investigating the potential of different parts of medicinal plants in the conservation agricultural system | ● Similar drug activity of stem-leaf and root system, with this difference that the stem-leaf was more stable in harvesting | (Chen et al., 2016) |

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***Conflict of Interest***
The authors indicate no conflict of interest in this work.

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