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RESEARCH ARTICLE

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Mathematical model-based redesign of chickpea harvester reel

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Abstract

Aim of study: This paper presents a mathematical modeling approach to redesign the reels of chickpea harvesters for harvest efficiency.

Area of study: A prototype chickpea harvester was designed and evaluated on the Dooshan farm of the University of Kurdistan, Sanandaj, Iran.

Material and methods: The strategy used for reducing harvesting losses derived from the dynamic study of the reel applied to the chickpea harvester. The machine was designed such that bats of a power take-off (PTO)-powered reel, in conjunction with passive fingers, harvest pods from anchored plants and throw the pods into a hopper. The trochoid trajectory of the reel bats concerning reel kinematic index, and plant height and spacing was determined for redesigning the reel.

Main results: This kinematic design allowed an estimation of the reel orientation at the time of impact. The experimentally validated model offers an accurate and low computational cost method to redesign harvester reels.

Research highlights: The new chickpea harvester implemented with a four fixed-bat reel, a height of 40 cm above the ground for the reel axis, and featuring a kinematic index of 2.4 was capable of harvesting pods with harvesting efficiency of over 70%; a significant improvement in harvesting performance.

Additional key words: chickpea harvesting; combine harvester modeling; harvesting losses; machine design; pulses.

Authors' contributions: The four co-authors participated in all stages of the work, including the conception and design of the research, the revision of the intellectual content and the drafting of the paper. All authors read and approved the final manuscript.

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Introduction

The nutritional value of legumes was recognized by the 68th general assembly of the United Nations in declaring 2016 as the International Year of Pulses (FAO, 2016). Chickpeas (*Cicer arietinum* L.) rank third worldwide among pulse crops, accounting for 10.1 million tons annually. India, Pakistan, and Iran are the largest producers with over 70 %, 10 %, and 5 % of total world production, respectively (UCDavice, 2014; Muehlbauer *et al.*, 2017). Small plants with pods close to the ground impede mechanical chickpea harvesting (Haffar *et al.*, 1991; Bansal *et al.*, 1992; Golpira, 2009; Modares Motlagh *et al.*, 2018; Shahbazi, 2018). As chickpeas are becoming more important in the world markets (The Atlantic, 2019), agricultural breeding programs (Grossman *et al.*, 2012; Kanouni *et al.*, 2014; Jayalakshmi, 2016; ICARDA Communication Team, 2019), and efficient harvesting machinery (Dhimate *et al.*, 2018; Singh *et al.*, 2018) would greatly benefit rural chickpea growers who account for almost 50 % of the total production costs for hand harvesting (Haddad *et al.*, 1988). Hand laborers collect the entire chickpea bush into central heaps for transport to a stationary thresher got grain separation (Paulsen *et al.*, 2015). Harvesting the entire plants including roots takes 6 to 8 man-days to harvest 1 ha (Golpira *et al.*, 2013). During hand harvesting, losses can range from 4 % to 15 % (Haddad *et al.*, 1988). Uprooting the bushes removes the nitrogen-fixing bacteria nodules, increases soil erosion, and decreases the following wheat rotation yield.

Pulse harvesting in developed countries is fully mechanized; either by direct combining, or more often, by mowing and swathing followed by combining (Siemens, 2006). Harvesting the seed at 18% moisture content reduces field losses through the combine harvesters (Fleury, 2015). The key to a successful mechanical harvest begins with good weed control to provide a mostly clean and uniform field that is ready for machine harvest. Since chickpea has an indeterminate growth habit, late-season precipitation after initial flowering and seed set can cause the plants to begin to regrow and flower again which complicates mechanical harvesting. In years where there are significant regrowth and flowering, herbicides are sometimes used to terminate the plants to help make it possible to mechanically harvest the seed (McVay, 2019). Desiccants and pre-harvest perennial weed controllers that aid in the preparation for pulses combining are presented by Saskatchewan Pulse Growers (2020). Smart sprayers can reduce the environmentally harmful effect of herbicides (Carballido *et al.*, 2013; Aravind *et al.*, 2017; Saiz-Rubio *et al.*, 2020).

However, the application of grain combine harvesters for harvesting rain-fed chickpeas cultivated in dry or semi drylands were restricted due to high harvesting losses. As stripping only pods can reduce pulse crop losses (Behroozi & Huang, 2002; Sidahmed *et al.*, 2004; Golpira, 2009; McVay, 2019), accompanying passive fingers with bat type reels (Golpira, 2013; Golpira *et al.*, 2013) should increase work quality of chickpea harvesting. A tractor-propelled harvester was fabricated with a semi-mounted chassis in which several bats of a reel, in conjunction with forward-oriented V-shaped slots, detached pods from anchored plants. The crop was conveyed over the finger and up the platform deck by the reel to the reservoir tank. Equipping the design with air reels (Golpira, 2015; Yavari, 2017; Modares Motlagh *et al.*, 2018; Zobeiri *et al.*, 2020) were reported for increasing harvesting performance. However, in low-density crops, *i.e.*, rain-fed chickpeas, stripper headers cannot produce a continuous flow of material and cause high gathering losses. Table 1 summarizes existing methodologies, that take advantage of reels to guide crop and reduce shattering losses, for chickpea harvesting.

Literature review on the existing mechanism for harvesting rain-fed chickpeas concludes high shattering losses which are the main contribution of the reels. Several research works, *e.g.* (Oduori *et al.*, 2008, 2012a,b), developed models to study the interactions between the crops *i.e.*, wheat and rice, and a combine harvester reel. A mathematical-based model of soybean harvester reels, which neglects the effects of the number of bats, was presented by Quick (1972). Reel diameter, number of bats, reel angular velocity, reel kinematic index, crop physical characteristics including plant height and distances in rows, and header height were found to be the most design factors affecting harvesting losses (Beard *et al.*, 1992; Sakai *et al.*, 1993; Hirai *et al.*, 2002a,b; 2004), and therefore design parameters for this research.

The objective of this study was to test a prototype tractor-mounted chickpea harvester for harvest efficiency. Mathematical modeling of the reel provided the reel bat trajectory to minimize losses.

Material and methods

Background

Figure 1 pictures an average plant of Kabuli variety and its simplified model. Data was gathered during ten years of measurement on chickpea plants in the field. Harvesting at 5 cm height would theoretically result in zero-remaining pods on anchored plants. In real field evaluations, however, the situation is more complex because it is influenced by the soil preparation system, the crop planting method, and the plant-harvester interaction. The average height of chickpea plants in non-irrigated chickpea fields was 30 cm. The maximum height of plants is important for ensuring that the traveling direction of the harvested material after interacting with the bats is sufficient to carry the harvested material to the hopper.

Reel modeling

Figure 2 is a schematic drawing of the reel components, with the location of the bats, and how the reel diameter was measured. A Cartesian coordinate system was applied to the positive X-axis horizontally to the right and the positive Y-axis vertically directed upward. The peripheral diameter is assumed to be equal to the reel diameter.

Figure 3 shows the hit points of the reel bat for both low and high crops on a vehicle-fixed coordinate system. The forward speed of the harvester does not affect X'_R, but it determines the global position (X_R, Y_R) of the vehicle coordinates.

The spatial curve path of the reel bats, as well as the velocities, were employed to design the optimum reel. Using ground-fixed coordinates, the position of any point

Table 1. The existing mechanisms, concepts, and accessories for chickpea harvesting

Mechanism	References
Grain combine harvesters	Haffar *et al.*, 1991; Siemens, 2006; Yavari, 2017; Duckfootparts, 2018; Primarysales, 2018; Awsairbar, 2019; Biso GmbH, 2019; MacDon Industries Ltd., 2019
Modified stripper headers	Behroozi *et al.*, 2002; Golpira, 2013, 2015; Golpira *et al.*, 2013; Modares Motlagh *et al.*, 2018

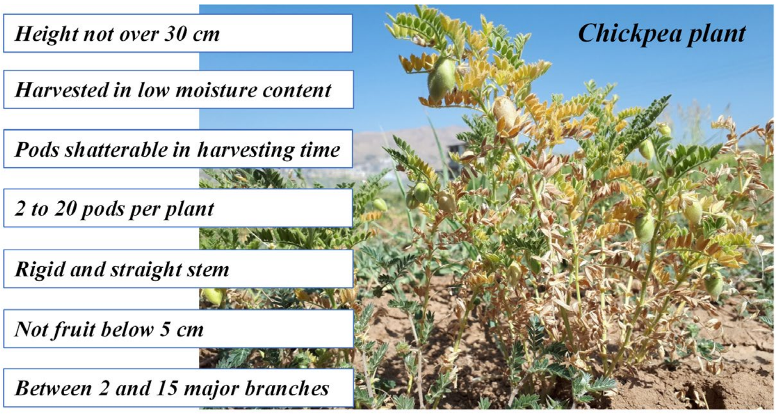

Figure 1. A working model for a chickpea plant that is favorable from the harvesting point of view.

on the absolute path of the reel bat can be determined according to the following expressions:

$$X_R = R\cos\frac{\omega t}{m} + Vt = X'_R + Vt \quad (1a)$$

in which

$$X'_R = R\cos\frac{\omega t}{m} \quad (1b)$$

and for vertical position, one could write

$$Y_R = H_R + R\sin\frac{\omega t}{m} \quad (2)$$

where X_R and Y_R are positions of bat edge, meter; ω is the angular velocity of an arm, Rad/s; H_R is the height of reel axis above ground, meter; m is the number of bats; and t is time, s. As the number of bats m grows, α decreases (Fig. 4), and therefore $\alpha = \omega t/m$. For low crops, if the number of bats increases to infinity ($m = \infty$), the following situation applies:

$$\lim_{m\to\infty} X'_R = R\cos 0 = R \quad (3)$$

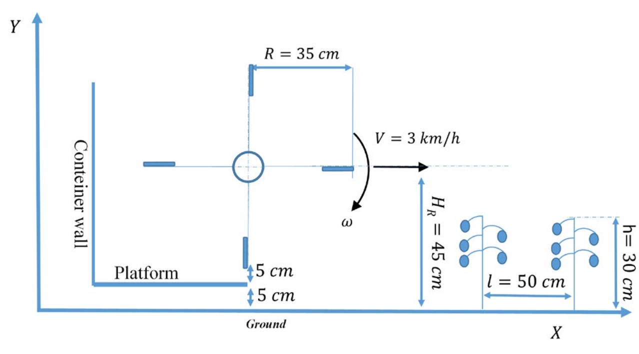

Figure 2. The reel of the developed chickpea harvester with the coordinate reference frame and the parameters relevant to machine design. H_R, height of reel axis above the ground; h, plant height; l, distance between two successive plants; R, reel diameter; V, tractor forward speed; w, angular velocity of an arm.

and

$$\lim_{m\to\infty} Y_R = H_R \quad (4)$$

Figure 3 demonstrates equations 3 and 4 are valid if the crop height is more than the height of the reel axis of rotation above the ground ($h \geq H_R$). For short plants and a given harvester, if $h < H_R$, the solution would be $Y_R = h$. Figure 4 shows the boundary situation for one bat in which crop height is equal to the position of the reel's central axis above the ground. For other cases with a larger number of bats, α depends on h and H_R. The situations demonstrated how important bat number (m) was for chickpea detachment by efficiently capturing and drawing them into the conveyor belt, the principal method for reducing yield losses.

The dynamic study of the reel may be expanded if the spacing between consecutive chickpea plants is varied. For example, in the Kurdistan region plant spacing is 50 cm. The time elapsed between two consecutive chickpea plants as the harvester moves at a forward speed V can be calculated from the following equations:

$$t = \frac{l}{V} \quad (5)$$

and

$$t = \frac{\alpha}{\omega} \quad (6)$$

where t is the time elapsed between two consecutive chickpea plants when the harvester moves at V speed, s; and α is sweep angle in time t, Rad. The left-hand side of equations 6 and 7 is the same, and hence one has,

$$\frac{l}{V} = \frac{\alpha}{\omega} \quad (7)$$

To hit each plant at the optimum position, each α requires a bat configuration based on the field parameters. At least 2 bats (integer > 1.8) are required for harvesting rain-fed chickpeas spaced at 50 cm, when forward speed is 3 km/h (0.83 m/s), and the reel rotational speed is 55 rpm.

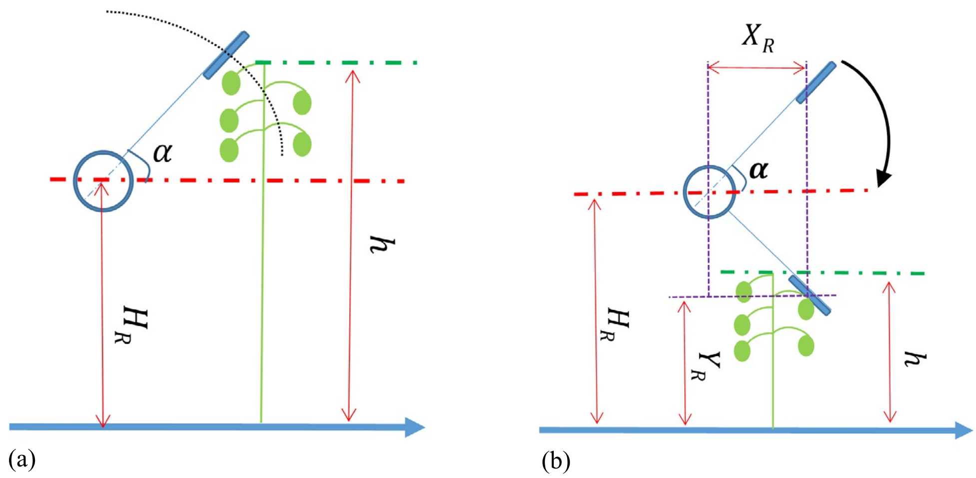

Figure 3. Bat hit points for tall plants (a) and short plants (b). X_R and Y_R, coordinates of bat edge; H_R, height of reel axis above ground; *h*, plant height; *m*, number of bats; *t*, time; *ω*, angular velocity of an arm; α, sweep angle.

However, as 4 bats produce a better-balanced reel, a better configuration would be 4 bats, reduce the reel spin to 25 rpm, coinciding with a bat for each plant spaced at *l*.

Prototype chickpea harvester

The tractor-propelled harvester introduced by Golpira (2013) and Golpira *et al.* (2013) was redesigned concerning reel and its power transmission mechanism. The tractor-propelled harvester was fabricated with a semi-mounted chassis in which several bats of a reel, in conjunction with forward-oriented V-shaped slots, detached the chickpea pods from the bush. The height-adjustable reel delivers the harvested material into the hopper. The main components of this harvester are: a transversely elongated frame fixed to a platform, protruding fingers extending forward over the platform, a reel driving system, a belt-drive, and two pivoting front wheels (Fig. 5). The designed reel consisted of a rotating shaft with rigidly mounted bats on radial arms that pushed the top of the chickpea plants over the platform. The platform design and characteristics described by Golpira & Golpîra (2017). The wooden bats were fixed by bolts on the steel structure of the reel. Two adjustable screws supported two pneumatic wheels which set the working height of the header from 0 to 150 mm. Moreover, these tires guide the platform on ground unevenness to avoid entering stones into the header. Width, length, and height of the machine are 2200, 1000, and 1000 mm, respectively. The working width of the machine is 1400 mm. Additional screws on the reel allowed for further positioning adjustments. The total weight of the machine was 400 kg.

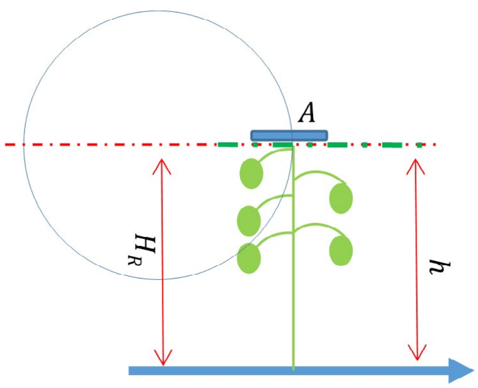

Figure 4. Reel bat hit point for tall crops and a large number of bats. *A*, bat hit point; H_R, height of reel axis above ground; *h*, plant height.

The pulley propelling the reel was located on one end of its rotating shaft, and a tractor-mounted power take-off (PTO) shaft. A gearbox with a conic gear allowed changing the axis direction 90° without modifying the speed ratio was attached to a variable-speed transmission assembly and a V-belt drive connected to the reel, as shown in Fig. 6. This continuously variable transmission system provided a gentle variation in the reel rotational speed with a maximum reduction ratio of 2.1:1. Alternative speed reduction ratios could be produced through the V-belt drive system up to a ratio of 1:5. This transmission reduced the initial 540 rpm supplied by the standard tractor PTO shaft to the 45-110 rpm working interval needed by the reel.

An essential requirement for satisfactory reel performance is that its kinematic index, defined as the ratio of peripheral to forward speed must be greater than one. When the forward speed of the reel is greater than the forward speed of the harvester, the trajectory of the reel is a trochoid (Miller *et al.*, 1990). The kinematic index of the reel was calculated as follows:

$$\lambda = \frac{Rn}{9.5V} \tag{8}$$

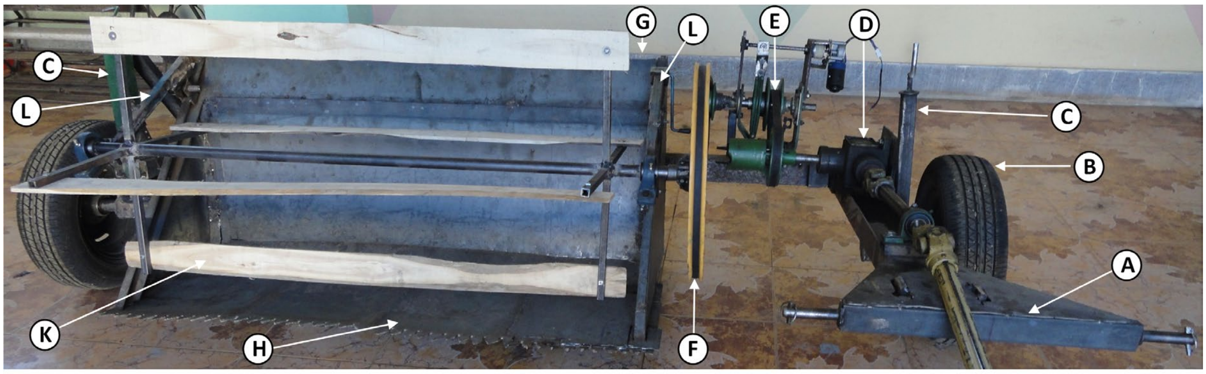

Figure 5. Prototype chickpea harvester: A, semi-mounted linkage; B, tire wheel; C, adjustable screw; D, gearbox; E, CVT gearbox; F, driven pulley; G, hopper wall; H, platform; K, reel bat; L, reel position adjusting screw.

where V is the forward speed of harvester, m/s; λ is the kinematic index; n is reel speed, rpm; and R is reel radius, meter.

The chickpea harvester was tested at a fixed ground speed of 3 km/h. The reel was adjusted so that the bats passed approximately 5 cm above the fingers. The reel distance ahead of the finger was fixed at 5 cm. The tilt angle of the platform, *i.e.* the angle of the platform to with the ground above a horizontal transverse axis, was adjusted to 0°.

Experimental area and layout

The trials were conducted on the Dooshan farm of the University of Kurdistan (Fig. 7) in July 2017. Cultivated areas of 93,112 ha and 676 ha of rain-fed and irrigated chickpeas in Kurdistan province (34°- 36° N latitude and 45°- 48° E longitude) produced 33,977 and 884 tons/year, respectively (Ahmadi, 2016; Managing and Planning Institute, 2016). A one-hectare plot was ploughed, disk-harrowed, and sown with the Kabuli chickpea. Plant and row spacing were 50 cm and 50 cm, respectively. The moisture content of the seeds was measured by drying the chickpeas in an oven at 105 °C for 72 hours. The moisture content recorded in harvesting time was approximately between 12 % and 15 %.

The high cost of field evaluations required a simple experimental design. The machine harvested 10 m field runs from three different points. Weeds were removed before the evaluation. Harvesting losses were estimated by collecting the pods and seeds remaining on the ground from a sample area 1.0 m long × 1.0 m (2 rows), wide. For each 10 m run, three samples separated by 2 m were collected. Samples were threshed, cleaned, and weighed to determine an average harvesting loss. Harvested pods were manually removed from the hopper by hand. Plants were manually harvested and threshed to determine harvestable yield for the field. Pre-harvest losses, the pods and seeds that fell to the ground before harvesting, were not included in total yield weight in the denominator. Harvester losses were calculated as a percent of harvestable yield by dividing lost seeds by manually harvested yield and multiplying the result by 100. The methodology for determining header losses was described by Paulsen *et al.* (2014).

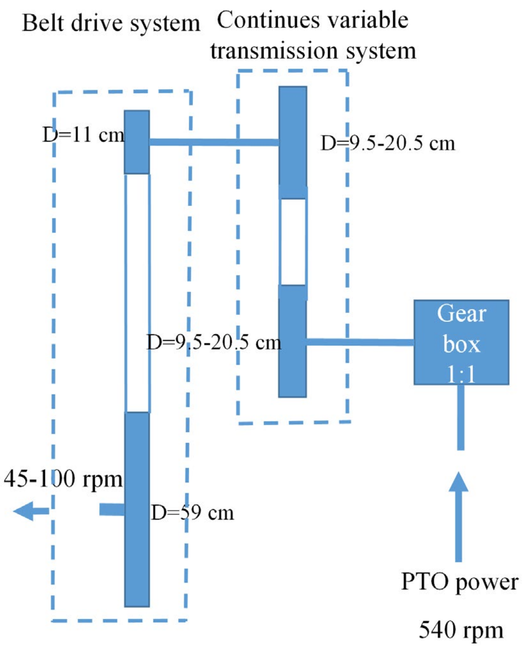

Figure 6. Schematic view of the power transmission system including a gearbox, a continuous variable system, and a belt-driven system to provide configurations of reel kinematic index. *D,* pulley diameter.

Results

Using Eq. (8) with a reel diameter of 0.7 m, a forward speed of 3 km/h, and a reel rotational velocity of 55 rpm, the kinematic index for the reel was 2.4. Figure 8 shows the trajectory of the reel with four fixed bats, a peripheral diameter of 70 cm, and a forward speed of 3 km/h. The arrows in the curve indicate the direction of the moving pods after being hit by reel bats. The critical height for the chickpea

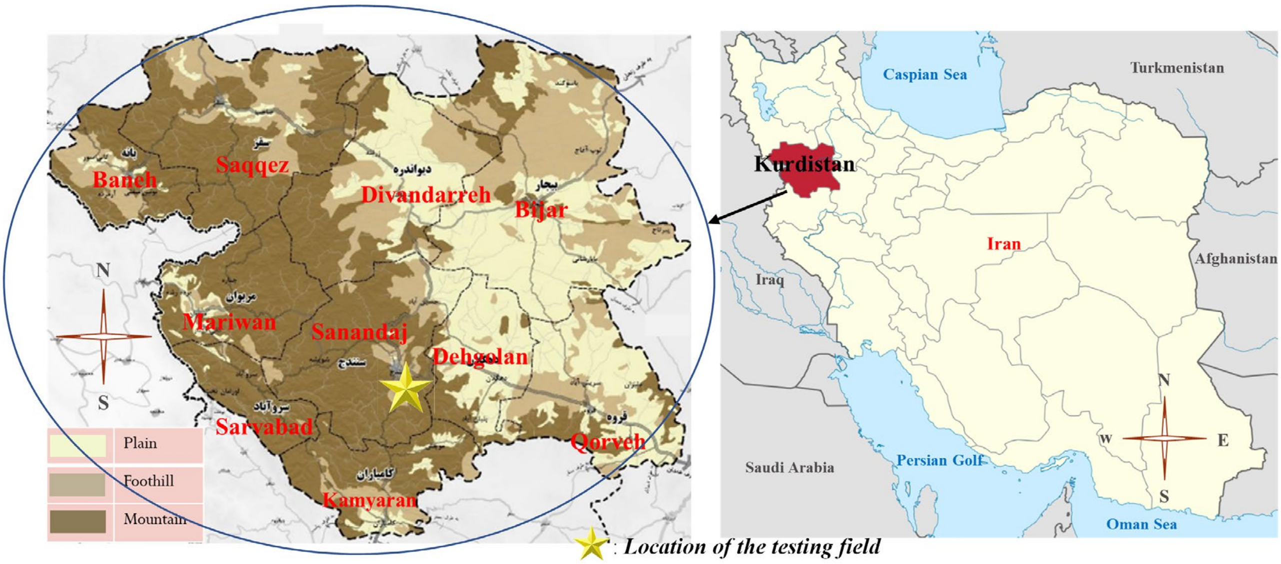

Figure 7. Location of the testing fields in the Dooshan farm of the University of Kurdistan.

plants was about 40 cm to assure the proper rearward velocity for harvested material to reach the harvester hopper.

Figure 9 shows the trajectory of the front point of a bat for a reel with four (m=4) and six (m=6) bats, and a kinematic index of 2.4 (Eq. 3). The trochoid trajectory of a single bat (m=1) reel was also plotted in Fig. 9 for comparison with the other configurations. Considering fixed-bat reels, a harvester speed of 3 km/h, and the corresponding reel index of 2.4, the harvested material is forced in the negative X direction towards the hopper, which only occurred for 4 and 6 bats. Kinematic indices of 1.1 to 3.4 were suggested for a 1.1 m diameter reel operating over a range of ground speeds where an index of 1.25 to 1.5 is recommended for standing crops (Miller *et al.*, 1990).

The reel bats beat the crop at the moment which its velocity vector has a negative X component. The location

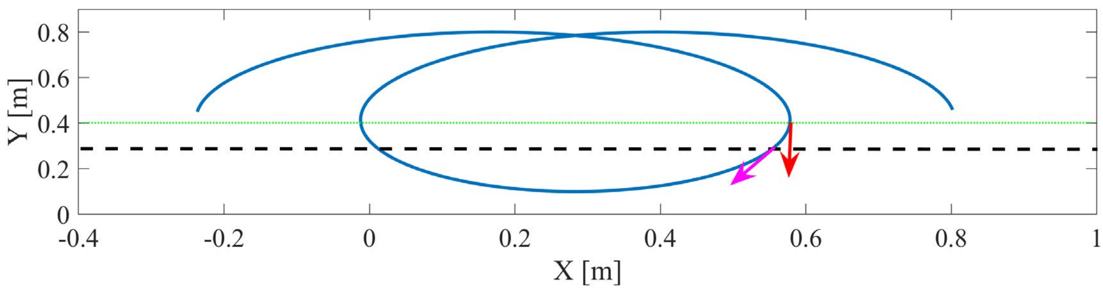

Figure 8. The trochoid trajectory of the reel with four fixed bats, a peripheral diameter of 70 cm, and a forward speed of 3 km/h.

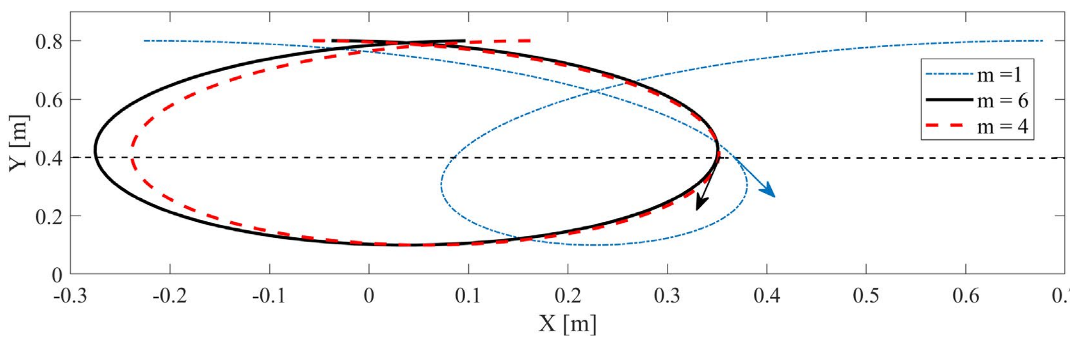

Figure 9. Trajectories of the reel with six, four, and one bat for a forward speed of 3 km/h and kinematic index of 2.4. The horizontal dashed line shows a plant height of 30 cm, the maximum height of field plants; *m*, number of bats.

of this point can be calculated by setting to zero the derivative of equation (1) for t, as given by equation (9):

$$\frac{dx}{dt} = -Rm\omega \sin(m\omega t) + V = 0 \qquad (9)$$

Substituting Eq. (4) in (2) determines the critical height of 42.7 cm and 41.4 cm above the ground for six and four bats, respectively. At this height, the velocity component of the reel bats in the X direction is zero, which is essential for reels of combine harvesters to reduce shattering losses. The mathematical modeling of the trajectory described by reel bats provided the recommended height of 40 cm above the ground for the reel axis.

Discussion

Following the successful prototyping of a chickpea harvester by Golpira (2013) and Golpira *et al.* (2013), this paper aims to derive an experimentally validated model for reel design. The mathematical model representation of the reel bats' trajectory suggested a height of 40 cm above the ground for the reel axis. Further, the kinematic analysis of the model concerning spacing between consecutive chickpea plants and spatial curve path of the reel bats configured a four-batted design.

Field evaluation of the prototype chickpea harvester confirmed that fixed-bat reel with a kinematic index of 2.4 harvested rain-fed chickpea pods with 71 % yield efficiency. While losses of more than 29% were also reported for the mechanized harvesting of irrigated chickpeas (Haffar *et al.*, 1991; Siemens, 2006; Jayalakshmi, 2016), comparing harvesting losses of rain-fed and irrigated chickpeas does not make sense as there is a significant difference between the crop properties. More precisely, while the prototype chickpea harvester could be used for harvesting both the irrigated and rain-fed farming, the application of the combine harvester is limited to the irrigated chickpeas, due to the plant height. This means that the proposed method in this paper makes a significant contribution over the literature.

Equipping the header with air reels, knife guards, and duck foot fingers, introduced by (Duckfootparts, 2018; Primarysales, 2018; Awsairbar, 2019), together with evaluating of the flexible and height-adjustable reels *i.e.*, 3D Varioflex header (Biso GmbH, 2019; Eggerding, Austria) and D65 draper header (MacDon Industries Ltd., 2019; Manitoba, Canada) is a forward step toward the mechanical harvesting of rain-fed legumes in dry and semi drylands.

The proposed mathematical model-based design of the reel not only reduced the design time and cost, but also increased harvesting performance of the prototype chickpea harvester. The modified tractor-propelled stripper harvester with reel bats and passive fingers effectively stripped chickpea pods from the bushes in the field. With a forward speed of 3 km/h and a 1.4 m working width, the theoretical field capacity for the prototype harvester is 0.42 ha/h.

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