

30 categorized into four primary stages, **which included** (1) soil preparation, (2) planting, (3) **growing**
31 (comprising irrigation, fertilization, pesticide application, and ratooning), and (4) harvesting
32 (involving cutting, loading, transportation to the factory, and unloading) (Monjazi et al., 2017).
33 These operations are characterized by substantial traffic of heavy machinery across various
34 production operations, particularly during cultivation and harvesting, and often practiced under
35 unfavorable moisture conditions. This could result in soil compaction. However, it is well known
36 that, soil compaction **can reduce** crop yields (Shaheb et al., 2021). Therefore, it is necessary **to**
37 **develop** an effective **cultivation** system with minimum soil compaction.

38 The nature of soil tillage operations for sugarcane land preparation is energy-intensive, time-
39 consuming and expensive. To reduce energy and time it is **necessary** to use conservation tillage as
40 well as controlled-traffic systems. In conservation sugarcane farming system, zonal or strip tillage
41 is when only the row area is cultivated in preparation for planting the sugarcane sett and the inter-
42 row area remains undisturbed and used as traffic zone. Therefore, strip tillage represents a farming
43 method that combines the advantages of reduced tillage for crop rows, with the benefits of no-till
44 in the inter-row spaces (Voorhees, 1991; Licht and Al-Kaisi, 2005; Laufer and Koch, 2017).
45 Sugarcane harvesting involves the use of sugarcane harvesters and transport baskets and the
46 machinery traffic affects approximately 50% of the total field area. Consequently, the
47 implementation of traffic control principles becomes crucial. This approach entails segregating the
48 area required for crop growth from the region impacted by machinery traffic (Mouazen and
49 Palmqvist, 2015; McHugh et al., 2009 and 2020).

50 The adoption of traffic control methods can result in a remarkable reduction in energy
51 consumption, up to 23%, during crop production stages when compared to conventional random-
52 traffic farming (RTF) (Chen et al., 2008 and 2010).

53 In today's agricultural practices, there is growing interest in integrated tillage methods. Integrated
54 tillage approaches have gained prominence due to their ability to reduce operating time, fuel
55 consumption, and energy requirements (Prem et al., 2016). Essentially, integrated tillage combines
56 various operations to prepare the soil with desirable characteristics, intending to reduce costs and
57 operating times (Manian and Kathirvel, 2001). Integrated machinery tends to be more complex
58 compared to single-purpose machines but offers numerous advantages and greater efficiency
59 within a similar timeframe (Sahu and Raheman, 2006).

60 **Considering the heavy texture of the soils of North Khuzestan due to their high clay content**
61 **and the traffic of heavy machinery in unfavorable soil moisture conditions at the time of**
62 **harvesting, conventional sub-breakers is used to reduce dense layers of soil.**

63 Generally, four common types of subsoilers are used for deep tillage: the bulldozer ripper, the
64 conventional/winged subsoiler, the Para plow, and the bent leg subsoiler (Harrison and Licsko,
65 1989b; Harrison, 1990; Raper, 2005). In addition to the quantity and quality of the disturbed soil
66 volume; the choice of subsoiler for deep tillage depends on its critical depth, and the required draft
67 force; therefore, an ideal subsoiler has a greater critical depth and requires less draft force (**Godwin**
68 **and Spoor, 1977**).

69 The critical depth is the depth below which soil loosening does not occur and only soil smearing
70 and compaction is observed. In other words, the critical depth is the depth at which the soil no
71 longer creates a crescent failure radiating from just above the tine point but whose failure zone has
72 its base part way up the tine shank and the soil at the tine base starts to flow forward and sideways
73 rather than lifting upwards (Godwin and Spoor, 1977; Godwin and O’Dogherty, 2007).

74 The tine implements such as chisel or subsoiler, which are used for shallow and deep soil tillage,
75 are equipped with forward-sloping shares (**Hoseinian et al, 2022**). Recently, a new tine implement
76 with sideway shares has been introduced for shallow subsurface tillage. It was field-tested by Salar
77 et al. (2013) and the effect of geometrical variables such as rake angle, tilt angle and share size on
78 tool resistance forces and the soil disturbance areas were analyzed using discrete element method
79 (DEM) by Hoseinian et al. (2022).

80 In this research, the concept of the “sideway shares” was used for developing a new deep tine
81 implement (subsoiler) as part of a combined strip deep tillage machine for sugarcane fields. Thus,
82 the primary objective of the current study is to develop, and evaluate a combined tillage machine
83 equipped with a two-level deep tillage implements comprising the dual sideway-share subsoiler
84 and the winged subsoiler, cum with a set of discs for strip deep tillage in sugarcane fields. The
85 research aims to compare the performance of this machine with that of a conventional subsoiler in
86 sugarcane land preparation operation, considering performance factors such as draft force, area of
87 the disturbed soil, and specific resistance.

88

89

90

91 2. Materials and methods

92 2.1. Farm characteristics

93 The experimental tests were conducted in the fields of Imam Khomeini Sugarcane Agro-industry
94 (31°39′ - 31°55′N and 48°39′ - 48°48′E). The agro-industry Co. is situated in the Shoabiye region,
95 located approximately 30 km south of Shushtar city in Khuzestan province, Iran. For having soils
96 with different physical and mechanical characteristics, two fields, namely SC13-32 and B1-131,
97 were selected.

98

99 2.2. Selected soil physical properties

100 The physical properties of the soil, including soil texture and bulk density, were measured at three
101 layers: 0-200, 200-450, and 450-700 mm. To account for the influence of soil texture on bulk
102 density, relative bulk density (RBD) was employed (Eq. 1).

$$103 \quad RBD = \frac{BD}{BD_{REF}} \quad (1)$$

104 **Where**, BD represents the bulk density of the soil, while BD_{REF} signifies the reference bulk
105 density. Given the substantial clay content in the study fields, the Jones equation (Eq. 2) was
106 utilized to determine the reference bulk density.

$$107 \quad BD_{REF} = 1.985 - 0.00857clay\% \quad (2)$$

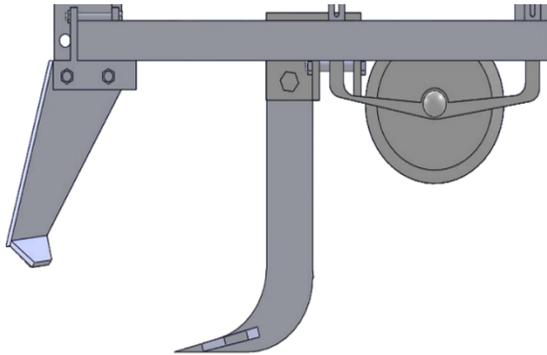
108 2.3. Specifications of the subsoiler used in conventional deep tillage in the sugarcane fields

109 In the sugarcane agro-industry Co. of Khuzestan, a conventional subsoiler with a curved (C
110 shaped) shank having a rectangular share with a rake angle of 18 degrees and without any wing is
111 used for deep tillage.

112

113 2.4. Specifications of combined two-level tilling machine for strip deep tillage of sugarcane 114 fields

115 The combined two-level tillage machine for strip deep tilling for the sugarcane fields, as depicted
116 in Fig. 1; includes two implements: 1) **the two** dual sideway share subsoiler in front and 2) the
117 winged subsoiler at a distance at the back on the machine frame. Additionally, a gang of discs is
118 mounted at the end of the frame to crush sugarcane residues.



119 **Fig. 1.** Combined two-level deep tillage machine cum with a conical-type disc gang.

120 For developing the dual sideway-share and winged subsoilers, several parameters were taken
121 into consideration. These parameters account for the physical and mechanical properties of the soil,
122 dimensions, rake angle, and the tilt angle of the shares and wings. Moreover, since the intended
123 tractor is a track-type bulldozer with an output power of 280 hp, it is crucial for the subsoilers not
124 only withstand compressive and tensile stresses but also be resistant to bending forces (resulting
125 from sudden twists of the bulldozer). To meet these requirements, ST52 alloy steel was used to
126 make the shares and wings.

127
128 **2.4.1. Specifications of dual sideway-share subsoiler**

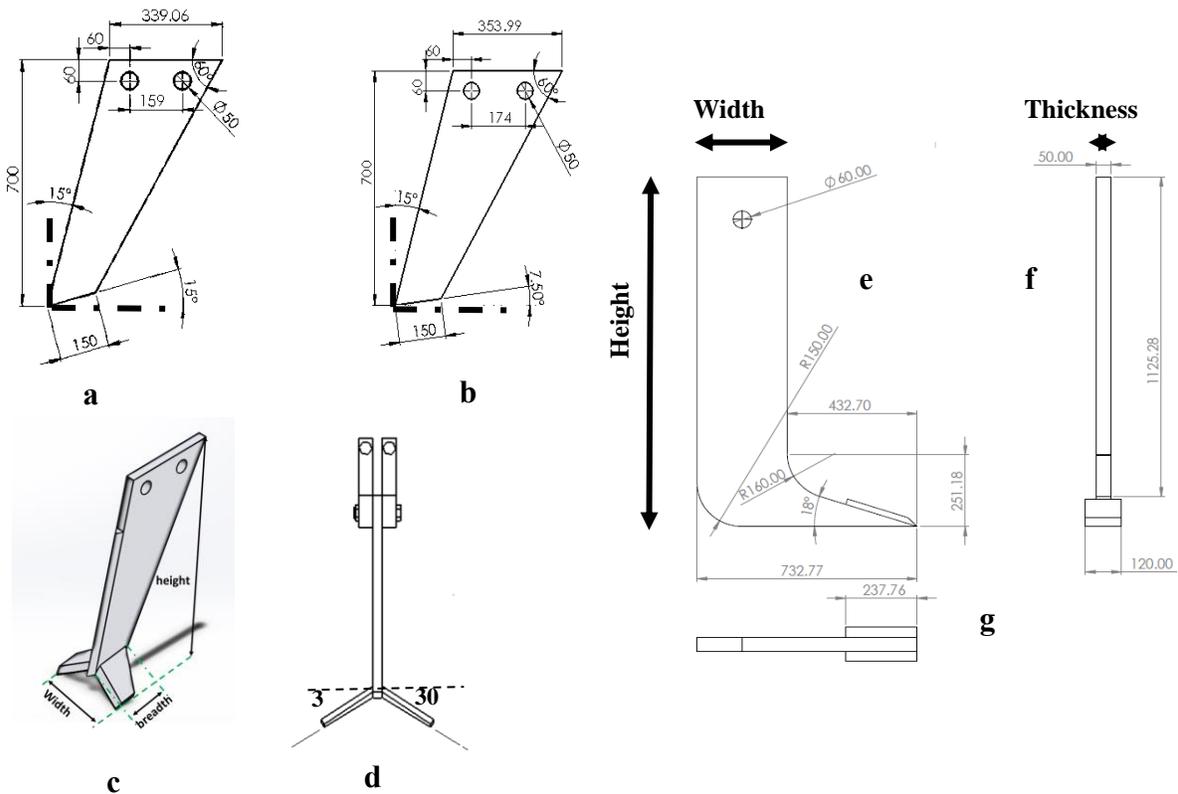
129 To determine the suitable geometry of the dual sideway-share subsoiler for achieving adequate
130 penetration into soil and having low specific resistance, the results of the discrete element method
131 (DEM) simulations of Hosienian et al. (2022) were considered. Their results stated that the draft
132 force increases with the increase of the rake angle and they considered the rake angle less than 15
133 degrees to be appropriate. Also, their results stated that different tilt angle do not have much effect
134 on draft force, but in the range of 20 to 30 degrees, it will bring minimum specific resistance. Two
135 rake angles, 7.5 and 15 degrees, were selected. In addition, considering the required tilled width of
136 the soil bed (800 mm) for planting two rows of plants on each bed, the shares with widths of 150
137 and 200 mm were tested. The angle of attachment of the shares to the shank (tilt angle) was set at
138 30°.

139
140

141 2.4.2. Specifications of winged subsoiler

142 To achieve subsoiling to a depth of 700 mm, a winged subsoiler having a share with an 18° rake
 143 angle was employed (Fig. 2). To provide the necessary disturbed soil volume in depth of root
 144 growth, three different wings with the lengths of 200, 250, and 300 mm were evaluated. The rake
 145 angle of the wings matched the subsoiler's share rake angle, which was 18°, and their tilt angle was
 146 set at 30°.

147



148 **Fig. 2.** Dimensional characteristics of the dual sideways-share subsoiler: a) 7.5° rake angle, b)
 149 15° rake angle, c) direction of subsoiler movement (dimensions in mm) and d) 30° tilt angle, and
 150 the views of the winged subsoiler having a share with an 18° rake angle from: e) front, f) right, and
 151 g) top.

152

153 2.4.3. Specification of disc gang

154 To break down the remaining clods and plant residues after subsoiling, four 710-mm (28-in)
 155 conical discs, manufactured from boron steel by O.F.A.S Italy, equipped with 230-mm spools,
 156 were used. The shaft of the disc gang was positioned at distances of 800 and 450 mm from the
 157 ground surface and the winged subsoiler, respectively (Fig. 1). Discs gang angle?

158

159 **2.4.4. Field evaluation of the combined deep tillage machine**

160 The field evaluation of different parts of the combined two-level deep tillage machine was based
 161 on specific resistance, which is obtained from the ratio of the draft force to the cross-sectional area
 162 of the disturbed soil. To measure the draft, two-tractor test (RNAM method) was employed. For
 163 this purpose, a load cell (S-shaped; H3-C3-20t-6B-D55 model) manufactured by Zemic Co,
 164 Germany was utilized. Data from the load cell were recorded using a data logger with a sampling
 165 rate of 1.0 s. The recorded data were stored on a 2-gigabyte memory card.

166 To measure the cross-sectional area of the disturbed soil, a profile meter with a width of 1000
 167 mm and a height of 800 mm was used. The calculation of the cross-sectional area of the disturbed
 168 soil was based on Equation (3).

$$169 \quad A = \left(\sum_{i=1}^n d_i \right) - (d_1 - d_n) \times L \quad (3)$$

170 **Where: A is the** area of disturbed soil in mm², **d_i is readings** taken from the profile meter rods
 171 **in mm, d₁ & d_n are readings** obtained from the first and last profile meter rods **in mm** and **L is the**
 172 longitudinal distance between the first and last profile meter rods, mm.

173
 174 **2.5. Statistical analysis**

175 Bulk density and relative bulk density at three layers of 0 to 200, 200 to 450, and 450 to 700 mm
 176 of soil, as well as draft force, area of disturbed soil, and specific resistance of the subsoilers, were
 177 assessed. This assessment was performed for the dual sideway-share subsoiler working to a depth
 178 of 450 mm, whereas for the winged subsoiler tilling to a depth of 700 mm. **the rake angle and**
 179 **lengths of the shares were consider for dual sideway-share subsoiler. Also, the length of the**
 180 **wings were considered for winged subsoiler. In each experiment a randomized completely**
 181 **block design** with three replications was used for field experiments. After checking the **normality**
 182 **of the data by Kolmogorov-Smirnov methods** and the uniformity of variances, an analysis of
 183 variance was conducted, and the means of the data were compared using the Duncan statistic in
 184 SAS software (Version 9.4) at 5 percent probability level.

185

186

187

188

189 **3. Results and discussion**190 **3.1. Soil texture and bulk density**

191 The texture, bulk density, and relative bulk density values at three soil layers in both fields are
 192 presented in Table 1. Both fields have the same soil texture, namely, silty clay. The results indicate
 193 that despite having similar soil texture, the two fields exhibit different bulk densities. Soil structure
 194 and texture largely determine bulk density. Therefore, the two fields differ and they do not have
 195 similar soil structures. Relative bulk density shows the compactness of the soil. The 0-450 mm and
 196 450-700 mm layers of the soil have different relative bulk densities. The average bulk density and
 197 relative bulk density across the 0-700 mm soil depth were 1.67 g cm⁻³ and 1.05 in the SC13-32
 198 field, while in the B1-131 field, they were 1.55 g cm⁻³ and 0.97, respectively. It is reported that the
 199 ideal soil bulk density for silt loams and silty clay loams should be less than 1.40 g cm⁻³, whereas
 200 the value of bulk density more than 1.65 g cm⁻³ restricts root growth (Anonymous, 2023).
 201 Therefore, bulk density values in all soil layers for both fields indicate that the soils are over-
 202 compacted. However, the SC13-32 field is more compacted than the B1-131 field.

203 **Table 1.** Soil texture, bulk density and relative bulk density in different soil layers in SC13-32 and
 204 B1-131 fields.

Field	Depth (mm)	Soil particle percentage			Texture	Bulk density (g cm ⁻³)	Relative bulk density
		Clay	Silt	Sand			
SC13-32	0-200	47	43	10	Silty clay	1.63b*	1.03b*
	200-450	47	43	10		1.62b	1.04bc
	450-700	49	43	8		1.67b	1.07c
B1-131	0-200	41	41	18	1.52a	0.93a	
	200-450	47	45	8	1.53a	0.97a	
	450-700	47	45	8	1.61b	1.02b	

*Mean values followed by the same letter in each column are not significantly different according to Duncan's new multiple range test at the 5% level of probability.

205

206 **3.2. Field performance of dual sideways-share subsoiler**

207 The cross-sectional areas of the disturbed soil for the subsoiler having two different share rake
 208 angles and lengths tilling 450 mm deep in both fields show that the implement was working above
 209 its critical depth (Fig. 3 and Table 2). This is due to the large width of the shares (with an aspect
 210 ratio greater than one and less than six, Godwin and Spoor, 1977), and therefore, the dual sideways-
 211 share subsoiler functioning as a narrow tillage tool and operating above its critical depth.

212 To determine the efficiency of soil loosening, the data of the measured draft force (Table 2) and
 213 the area of disturbed soil were analyzed and used to calculate specific resistance.

214 **Table 2.** Draft force (KN) and specific resistance (KN m⁻²) of the dual-sideway-share subsoiler in
 215 different soil.

SL (mm)	α (deg.)	Draft force (KN)		Specific resistance (KN m ⁻²)	
		SC13-32	B1-131	SC13-32	B1-131
150	7.5	19.51a	16.56a	96.70a	64.60a
200	7.5	22.34b	20.83b	101.30a	76.20b
150	15	30.90c	22.80b	138.50b	86.40b
200	15	37.57d	25.99c	149.40b	82.0b

Mean values followed by the same letter in each column are not significantly different according to Duncan's new multiple range test at the 5% level of probability. Explain the SL, α , SC13-32 and B1-131 here. The reader should not refer to the text to understand the table

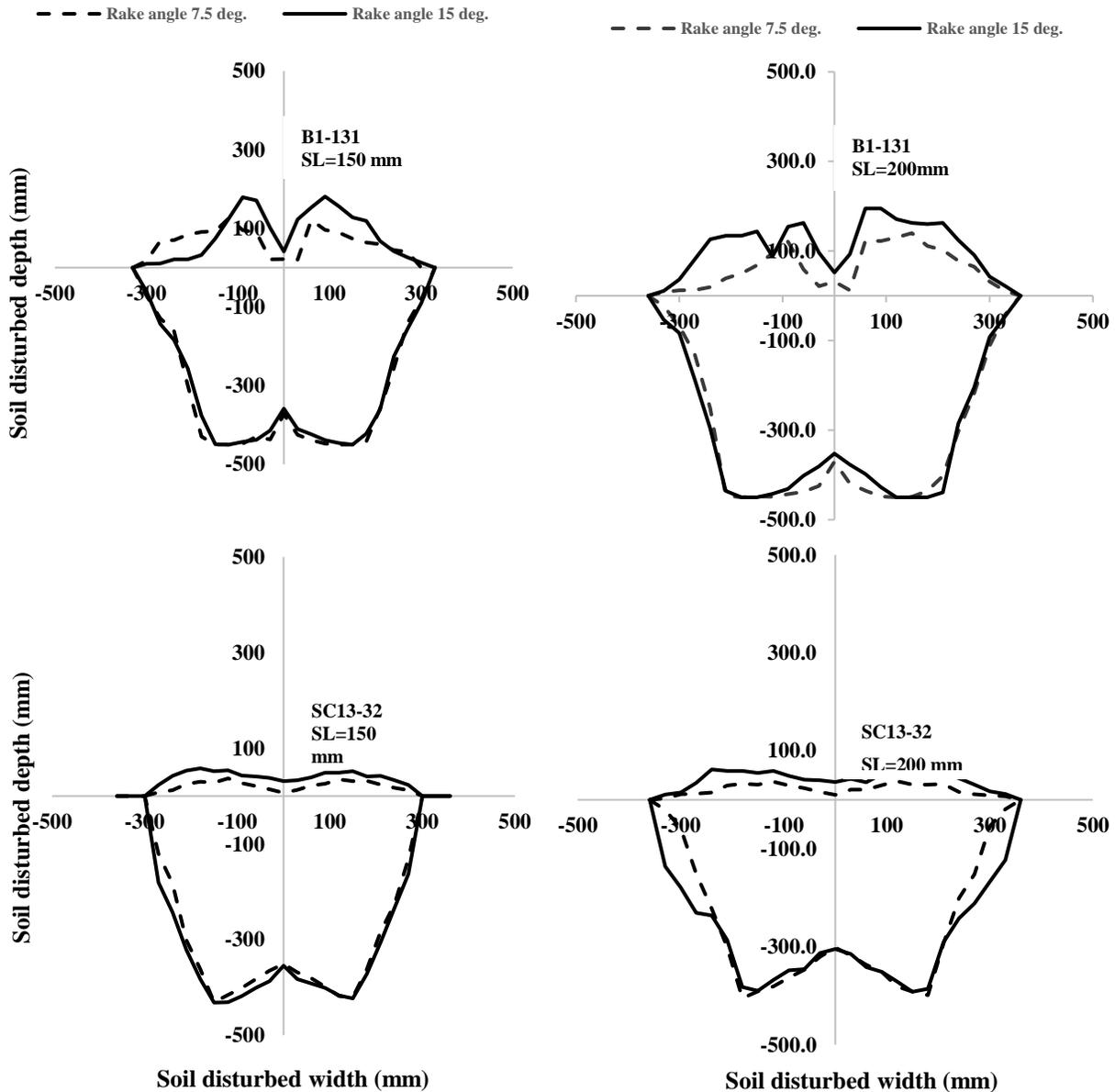
216 The field experiments indicated that an increase in the angle or length of the share resulted in a
 217 higher draft force requirement. The DEM simulation results given by Hosienian et al. (2022) also
 218 showed that the increase of the share rake angle or its cutting width linearly increased the draft
 219 force of a single sideway share subsurface tillage implement. Notably, the force value in the B1-
 220 131 field was significantly lower than in the SC13-32 field. Therefore, the SC13-32 field is more
 221 compacted than the B1-131 field as shown by measuring the soil bulk density (Table 1).

222 In the B1-131 field, which had lower soil bulk density compared to the SC13-32 field, there was
 223 a greater amount of disturbed soil and soil upheaval (height of accumulated soil on the surface).
 224 The smallest disturbed soil area was associated with the subsoiler having a share with a 7.5° rake
 225 angle and 150-mm length, while the largest disturbed soil area was related to the subsoiler featuring
 226 a share with a 15° rake angle and 200-mm length (refer to Figs. 3). Increasing the rake angle from
 227 7.5 to 15° did not significantly increase the width of the disturbed soil.

228 The lowest specific resistance was achieved with the dual sideway-share subsoiler equipped with
 229 a 7.5° rake angle and a 150-mm share length. Additionally, its value in the B1-131 field was
 230 significantly lower than in the SC13-32 field. Conversely, the highest specific resistance was
 231 observed in the soil of the SC13-32 field when using a 15° rake angle and a shared length of 200
 232 mm (Fig. 3). These results agree with the findings of Salar et al. (2013).

233 The selection of the optimal share dimensions was determined by comparing the specific draft
 234 (resistance) of the subsoiler equipped with different share sizes. The minimum specific draft was
 235 associated with the subsoiler having a share with a 7.5° rake angle and 150-mm length tilling soil
 236 in the B1-131 field. On the other hand, the maximum specific force was related to soil tillage using
 237 the subsoiler equipped with a share having 15° rake angle and 200-mm length in the SC13-32 field
 238 (Table 2). In growing two rows of sugarcane plants on a bed, for growth and development of the
 239 plant roots, a disturbed soil volume with a width of 110-cm and 45-cm depth is required (Sugarcane
 240 & by products development company, 2012). Therefore, to determine the optimal distance between

241 the two units (shanks) of the dual sideway-share subsoiler, the disturbed surface of the soil in depth
 242 and the possibility of passing sugarcane clods and stumps with a diameter between 30 and 40 cm
 243 were also taken into consideration. Therefore, the center-to-center distance of 50 cm was
 244 considered between the two shanks of the subsoiler (Figure 4); the winged subsoiler with a vertical
 245 shank, with working depth of 700 mm is mounted in the middle of the two shanks at the back of
 246 the machine frame.



247
 248 **Fig. 3.** The soil disturbed area (mm²) using the dual sideway-share subsoiler with different rake
 249 angles (α) and share lengths (SL) in both fields.
 250

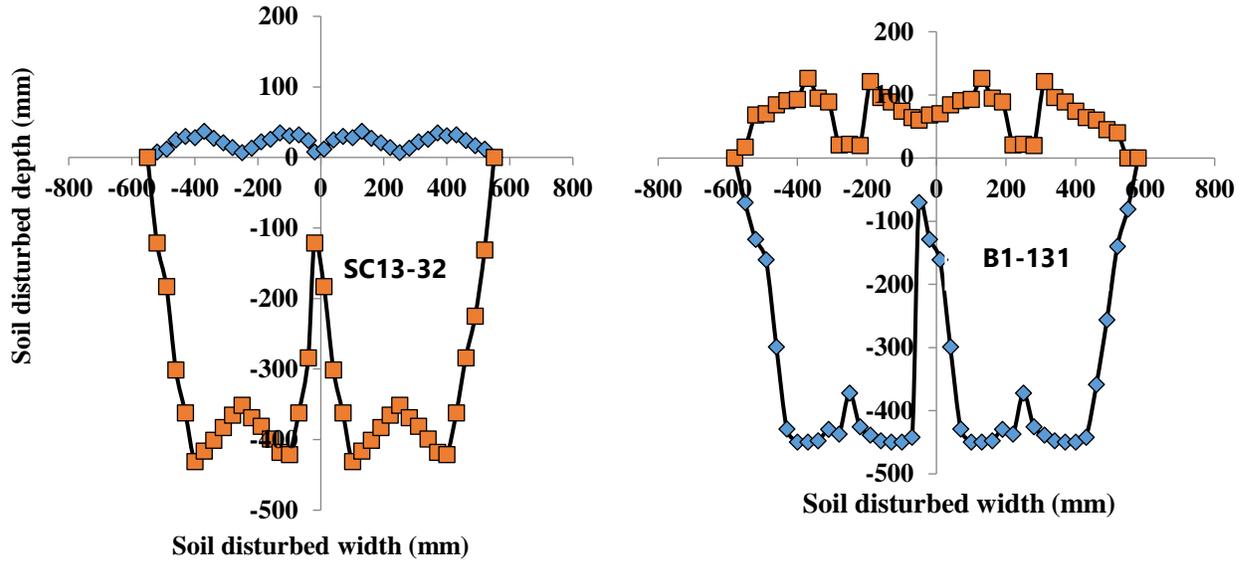


Fig. 4. The cross-sectional area of the disturbed soil and soil upheaval during deep tillage with two shanks of the dual sideway-share subsoiler. (Use same color to show soil upheaved and disturbed area. For example, use yellow dots for upheaved area at both diagrams and blue dots for disturbed area)

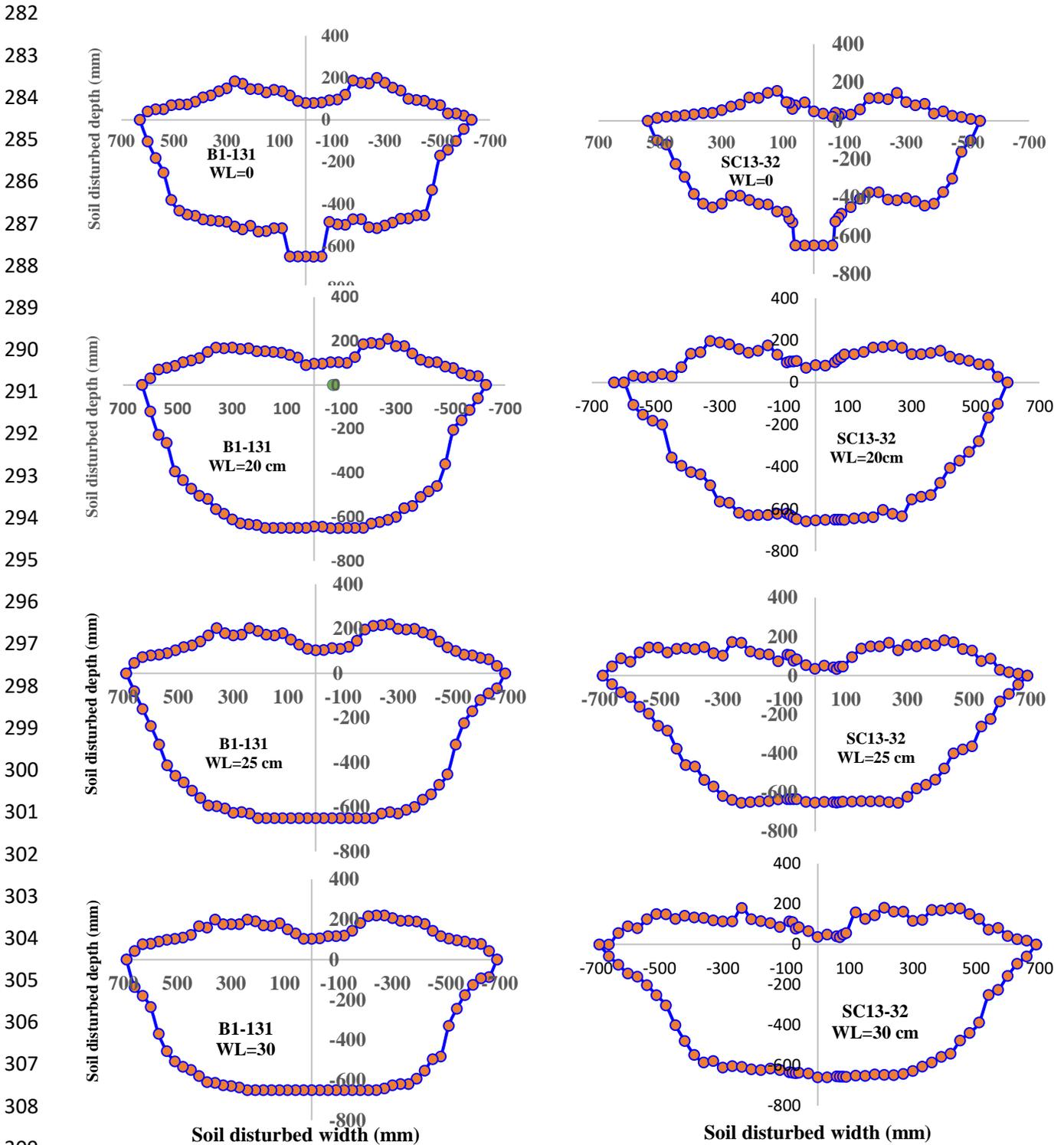
The specific resistance values for conventional and the dual sideway-share subsoiling at the depth of 450 mm are presented in Table 3. The results indicate that in the sugarcane fields of Khuzestan, the specific resistance of the dual sideway-share subsoiler is at least 20% and, in some cases, up to 30% lower than the conventional subsoiler working at 450-mm depth. Because using the dual sideway-share, the increase in soil rupture has exceeded the increase in tensile force.

Table 3. Specific resistance (kN m^{-2}) of the dual-sideway-share subsoiler as compared to the conventional subsoiler.

Fields	Dual-sided bent share	Conventional	Percentage of reduction
SC13-32	96.7	123.1	21.1
B1-131	66.7	96.1	30.20

3.3. Field performance of winged subsoiler and its optimum wing size

To evaluate the performance of the winged subsoiler, measurements were taken for the draft force, area of disturbed soil, and subsequently, computing its specific resistance. This assessment involved wings with lengths of 0, 200, 250, and 300 mm. To create similar soil conditions as those achieved by the combined two-level deep machine, first, the two units of the dual-sided bent share subsoiler were used to till the soil to a depth of 450 mm.



311 **Fig. 5.** Soil disturbance and upheaving in deep tillage using winged subsoil with different wing
 312 lengths.

313 The results of the disturbed soil area measurements using the winged subsoiler are presented in
314 Fig. 5. These results reveal that the critical depth for the wingless subsoiler is about 500 mm.

315 Below this depth, soil loosening (upheaving) does not occur, however, a channel with smeared
316 walls of the same width as the shank in the soil is created. Moreover, increasing the length of the
317 wing leads to increased soil disturbance volume. The area of soil disturbance and soil upheaval due
318 to varying wing length are summarized in Figure 5. The data shows that as the wing length
319 increases, both soil upheaval and the area of soil disturbance increase.

320 The results of the draft force and specific resistance for the winged subsoiler are presented in
321 Table 4. According to these findings, there is an upward trend in draft force as the length of the
322 wing increases. However, there were no significant differences in specific resistance between the
323 wingless and winged subsoilers. In other words, while increasing the wing length led
324 proportionately to a larger area of soil disturbance; it did not significantly affect the specific
325 resistance. Field observations revealed that in these clay-rich and compacted soils, no horizontal
326 cracks in the direction of the share (point) tip, as reported in other studies (Godwin and O’Dogherty,
327 2007), were observed. Therefore, each wing probably mimicked the behavior of the share (point)
328 in undisturbed soil, and the draft force as well as the volume of the disturbed soil increased
329 proportional to wing length. Consequently, adding wings did not reduce the subsoiler-specific
330 resistance.

331 **Table 4.** Draft force (KN) and specific resistance (kN m⁻²) of winged subsoiler in different soil.

WL (mm)	Rake angle (deg.)	Draft force (KN)		Specific resistance (KN m ⁻²)	
		SC13-32	B1-131	SC13-32	B1-131
0	20	18.93a	17.49a	32.27a	25.72a
200		22.23b	20.16b	30.83a	25.81a
250		26.65c	22.38c	33.73a	25.64a
300		28.41d	24.37d	35.51a	27.32a

Mean values followed by the same letter in each column are not significantly different according to Duncan's new multiple range test at the 5% level of probability. All parameters must be defined here.

332
333 In the sugarcane agro-industry Co. of Khuzestan province, two rows of sugarcane billets are
334 planted on each ridge (bed) with a horizontal spacing of 450 mm. additionally, each sugarcane
335 shoot requires a growing space with a radius of 250 mm to develop without competition. Since
336 70% of the sugarcane billet roots grow within the range of 0 to 450 mm deep in soil (Blackburn,
337 1984), it is recommended that strip tillage machine provides a bed with a width of 500 mm and a
338 depth of at least 450 mm for each sugarcane shoot. Therefore, based on the findings presented in
339 Table 4, it is advisable to use wings with a length of 250 mm. Furthermore, for both fields with

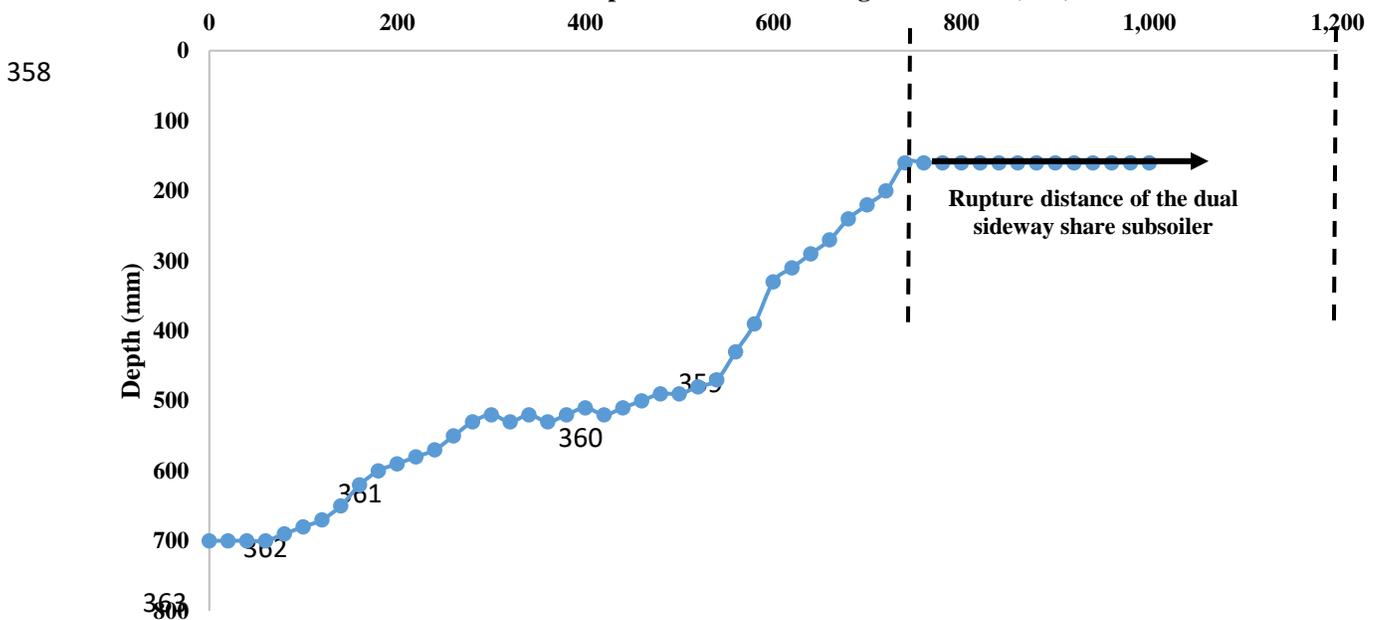
340 different bulk densities, using wingless subsoilers for strip tillage in sugarcane cultivation is not
 341 recommended.

342

343 3.4. Optimum positioning of the winged subsoiler on the combined machine frame

344 The efficiency of the subsoilers can be maximized while the longitudinal distance between the
 345 two is such that it allows the soil failure by the front subsoiler to stabilize before the rear subsoiler
 346 reaches it. Therefore, in determining the longitudinal spacing between the winged and the dual
 347 sideway-share subsoilers for developing a combined two-level deep tillage machine it was
 348 necessary to find out the forward “rupture distance” of the winged subsoiler. This ensures that the
 349 longitudinal rupture generated by the winged subsoiler intersects under the soil disturbance caused
 350 by the front subsoiler while avoiding interactions between the soil disturbances of both subsoilers
 351 (Fig.6). The findings indicate that the deep-working winged subsoiler disrupts the soil in front of
 352 itself, covering a distance of up to 740 mm (referred to as the rupture distance) from its share tip.
 353 Consequently, to enable independent soil tillage by both implements, there should be a minimum
 354 spacing of 740 mm between the shanks of the dual sideway-share subsoiler and the share tip of the
 355 winged subsoiler. This ensures that each tool can effectively perform its soil disturbance functions
 356 without interfering with the other.

357



364 **Fig. 6.** Forward soil disturbed by the winged subsoiler with a 250-mm wing.

365 **3.4. Conventional subsoiling versus strip subsoiling using the combined machine for**
 366 **sugarcane deep tillage**

367 The results of comparing the performance parameters of conventional subsoiling with the
 368 combined machine are presented in Table 5. The findings indicated that while the draft force
 369 required for the combined strip tillage tool in sugarcane cultivation is 29% higher than that of the
 370 conventional subsoiler, the amount of soil loosened in the strip tillage method is 90.54% higher
 371 compared to the conventional method. Therefore, the specific resistance of the combined deep strip
 372 tillage machine is 33.7% lower than that of the conventional deep tillage. Consequently, it is
 373 recommended to use the combined two-level strip deep tillage machine in sugarcane cultivation.

374 **Table 5.** Comparison of performance parameters of conventional subsoiler versus the combined
 375 two-level strip deep subsoiler.

Parameter	Tillage method	Conventional	Strip deep*	Percentage increase or decrease
Draft force (kN)		42.1	54.3	+29
Area of disturbed soil (m ²)		0.32	0.63	+90.54
Specific resistance (kN m ⁻²)		132	86.3	-33.7

*Includes two dual-bent share subsoiler shanks + a winged subsoiler + a four-disc gang.

376
 377 The obtained results are in line with the findings reported by Godwin and Spoor (1977). They
 378 observed that the addition of wings and surface-working tools in front of deep-working tools led
 379 to an increasing trend in draft force and the disturbed soil area. However, the specific resistance
 380 decreased compared to using a single deep-working tool. Moreover, the results obtained from this
 381 study are consistent with the findings reported by Gazor and Laghavi (2006). Therefore, strip
 382 tillage, which can create an optimal environment for sugarcane plant growth without transferring
 383 the compaction effect zone to the crop area, holds significant importance (Mcphee et al., 2020).

384 The results obtained from the effect of the rake angle on the draft force in deep tillage as compared
 385 to the results obtained in shallow tillage Hoseinian et al. (2022) showed that the minimum draft
 386 force was obtained at the same rake angle (7.5 degrees) for both shallow and deep dual sideways-
 387 share implements. **Askari et al. (2019) studied a new tiller, the bent-winged tines, and they**
 388 **found a 10-degree inclination angle to be appropriate compared to a 20-degree angle at 400**
 389 **mm depth.**

390
 391

392 **4. Conclusions**

393 The combined strip tillage machine equipped with two-level deep tillage implements comprising
394 a dual sideway-share subsoiler and a winged subsoiler, cum with a set of discs is a novel and
395 effective approach to deep tillage in sugarcane fields. Using this new tillage machine, in addition
396 to decreasing the production costs, the soil structural damages could be reduced. Based on the
397 results from the field experiments, the following conclusions were drawn:

398 1- The dual sideway-share subsoiler, with a 7.5° rake angle and 150-mm share length can
399 reduce specific resistance by more than 20% compared to conventional sugarcane deep tillage. For
400 strip tillage in sugarcane, the minimum distance between the two adjacent dual sideway-share
401 subsoiler's shanks should be 550 mm.

402 2- Deep tillage with a wingless subsoiler beyond its critical depth can promote soil
403 compactness, rather than removing compaction due to plastic failure of the soil around the share
404 and lower shank. Winged subsoilers can provide high levels of tillage efficiency and eliminate
405 critical depth issues, providing the wingspan is sufficient. The best wing for deep subsoiling in
406 fields with a high clay content is 250 mm in length.

407 3- To use two-level subsoiler for deep strip tillage, the first-level subsoiler should operate at a
408 depth of 450 mm, and the second-level deep subsoiler can operate at as depth as 700 mm.

409 4- Using the developed combined strip deep tillage machine compared to conventional
410 subsoilers demands more draft force but significantly increases soil disturbance, resulting in a
411 reduction of at least 33% in specific resistance.

412
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418
419 **References**

- 420 1. Anonymous, (2023). Soil health indicator sheet - Soil compaction (bulk density),
421 <https://stormwater.pca.state.mn.us> (Accessed on 28th of Oct., 2023).
- 422 2. Askrai, M., Shahgholi, GH. & Abbaspour-Gilandeh, Y. (2019). New wings on the
423 interaction between conventional subsoiler and paraplow tines with the soil: effects on the

- 424 draft and the properties of soil. *Arch Agron Soil Sci.*,1:88-
425 100.<https://doi.org/10.1080/03650340.2018.1486030>
- 426 3. Blackburn, F. (1984). Sugar cane. Longman, New York, ISBN: 0-582-46028-X, 414 pp.
- 427 4. Chen, H., Bai, Y.H., Wang, Q.J., Chen, F., Li, H.W., Tullberg, J.N., Murray, J.R., GAO,
428 H.W., & Gong, Y.S. (2008). Traffic and tillage effects on wheat production on the Loess
429 Plateau of China. 1. Crop yield and SOM. *Aust J Soil Res.*, 46: 645–651.
430 <https://DOI:10.1071/SR07106>
- 431 5. Chen, H., Wi, W., Liu, X.T., & Li, H.W. (2010). Effect of wheel traffic on working
432 resistance of agricultural machinery in field operation. *Nongye Jixie Xuebao*
433 (Transactions of the Chinese Society for Agricultural Machinery) 41: 52–57.
- 434 6. Croton., J.L., & Ainsworth, G.L. (2007). Development of a winged tine to relieve mining-
435 related soil compaction after bauxite mining in Western Australia. *Restor. Ecol.*, Vol.15,
436 No.4 (Supplement), pp. S48–S53. <https://doi.org/10.1111/j.1526-100X.2007.00292.x>
- 437 7. Durairaj, C.D., & Kumar, V.J.F. (1999). A discrete analytical procedure for predicting soil
438 failure patterns and reactions of bent leg ploughs. *Soil Tillage Res.*, 50:33-45.
439 [https://doi.org/10.1016/S0167-1987\(98\)00191-3](https://doi.org/10.1016/S0167-1987(98)00191-3)
- 440 8. Gazar, H.R. & Loghvi, M. (2006). The Effect of Surface Blades Strength and Physical
441 Properties of Soil. *Research and Development in Agriculture and Horticulture Journal.*,
442 73, 105-111. (In Persian).
- 443 9. Godwin, R. J. & O’Dogherty, M. J. (2007). Integrated soil tillage force prediction models.
444 *J Terramech.*, 44:3-14. <https://doi.org/10.1016/j.jterra.2006.01.001>
- 445 10. Godwin, R. J. & Spoor, J. (1977). Soil failure with narrow tines. *J Agric Eng. Res.*, 22(3).
446 213-228. [https://doi.org/10.1016/0021-8634\(77\)90044-0](https://doi.org/10.1016/0021-8634(77)90044-0)
- 447 11. Harrison, H. P. (1990). Soil reacting forces for two tapered bent leg plows. *Americ Soci*
448 *Agri Biologi Eng.*, 33(5):1473-1476. <https://doi:10.13031/2013.31496>
- 449 12. Harrison, H. P. & Licsko, Z. J. (1989b). Soil reacting forces for models of three bent leg
450 plows. *Soil Tillage Res.*, 15(1-2):125-135. [https://doi.org/10.1016/0167-1987\(89\)90069-](https://doi.org/10.1016/0167-1987(89)90069-X)
451 X
- 452 13. Harrison, H. P. & Licsko, Z. J. (1989a). Soil reacting wrenches and dynamics for three
453 models of bent leg plows. *Americ Soci Agri Biologi Eng.*, 32(1):50-53. [https://doi:](https://doi:10.13031/2013.30961)
454 10.13031/2013.30961

- 455 14. Hoseinian, S. H., Hemmat, A., Eshaghbeygi, A., Shahgoli, G. & Baghbanan, A. (2022).
456 Development of a dual sideway-share subsurface tillage implement: Part 2. Effect of tool
457 geometry on tillage forces and soil disturbance characteristics. *Soil Tillage Res.*,
458 <https://doi.org/10.1016/j.still.2021.105200>
- 459 15. Laufer, D. & Koch, H-J. (2017). Growth and yield formation of sugar beet (*Beta vulgaris*
460 L.) under strip tillage compared to full width tillage on silt loam soil in Central Europe.
461 *Europ J Agro.*, 82: 182-189. <https://doi.org/10.1016/j.eja.2016.10.017>
- 462 16. Licht, M. A. & Al-Kaisi, M. (2005). Strip tillage effect on seedbed soil temperature and
463 other soil physical properties. *Soil Tillage Res.*, 80:233-249.
464 <https://DOI:10.1016/j.still.2004.03.017>
- 465 17. Lovera, L.H., de Souza, Z.M., Esteban, D.A.A., de Oliveira, I.N., Farhate, C.V.V., de
466 Lima, E., S., & Panosso, A.R. (2021). Sugarcane root system: Variation over three cycles
467 under different soil tillage systems and cover crops. *Soil Tillage Res.*, 208, 104866.
468 <https://doi.org/10.1016/j.still.2020.104866>.
- 469 18. Monjezi, N., Zaki Dizaji, H., & Sheikh Davoudi, M. J. (2017). Scheduling sugar
470 production operations using GERT method (classical and fuzzy), Doctoral Dissertation,
471 Faculty of Agriculture, Shahid Chamran University of Ahvaz, Ahvaz. (In Persian).
- 472 19. Mchugh, A.D., Tullberg, J.N., & Freebairn, D.M. (2009). Controlled traffic farming
473 restores soil structure. *Soil Tillage Res.*, 104, 164–172.
474 <https://doi.org/10.1016/j.still.2008.10.010>
- 475 20. Mcphee, J.E., Antille, D.L., Tullberg, J.N., Doyle, R.B., & Boersma, M. (2020). Managing
476 soil compaction – A choice of low-mass autonomous vehicles or controlled traffic? *J*
477 *Biosys Eng.*, 195, 227–241. <https://doi.org/10.1016/j.biosystemseng.2020.05.006>
- 478 21. Manian, R. & Kathirvel, K. (2001). Development and evaluation of an active - passive
479 tillage machine. *AMA, Agric. Mecha. Asia, Africa and Latin America.*, 32(1): 9-18.
- 480 22. Mouazen, A.M., & Palmqvist, M. (2015). Development of a framework for the evaluation
481 of the environmental benefits of controlled traffic farming. *J Sustain.*, 7: 8684–8708.
482 <https://doi.org/10.3390/su7078684>
- 483 23. Prem, M., Swarnkar, R., Vyas, D. K., Pargi, S. J., & Khodifard, B. C. (2016). Combined
484 tillage tools: a review. *Cur Agri Res J.*, 4(2):179-185. <https://DOI:10.12944/CARJ.4.2.07>
485 55

- 486 24. Raper, R.L. (2005). Subsoiling, Encyclopedia of Soils in the Environment., 69-76.
487 <https://doi.org/10.1016/B0-12-348530-4/00267-8>
- 488 25. Sahu, R. K. & Raheman, H. (2006). Draught prediction of agricultural implements using
489 reference tillage tools in sandy clay loam soil. *J Biosys Eng.*, 94(2):275-284.
490 <https://doi.org/10.1016/j.biosystemseng.2006.01.015>
- 491 26. Salar, M. A., Esehaghbeygi, A., & Hemmat, A. (2013). Soil loosening characteristics of a
492 dual bent blade subsurface tillage implement. *Soil Tillage Res.*, 134:17-24.
493 <https://doi.org/10.1016/j.still.2013.07.005>
- 494 27. Shaheb, R.MD., Venkatesh, R., & Shearer, S.A. (2021). A Review on the effect of soil
495 compaction and its management for sustainable crop production. *J Biosys Eng.*, 46, 417-
496 432. <https://doi.org/10.1007/s42853-021-00117-7>
- 497 28. Sugarcane & by products development company (2012). Agronomic guideline for
498 sugarcane production., Volume 1.
- 499 29. Voorhees, W. B. (1991). Compaction effects on yield are they significant. *Amer Soci Agri*
500 *Biologic Eng.*, 34(4):1667-72. <https://doi:10.13031/2013.31786>

502 ساخت و ارزیابی زیرشکن دوسطح کار نواری در مزارع نیشکر

503 سینا لطیف التجار، و عباس همت

504 چکیده

505 در استان خوزستان تعداد تردد ماشین آلات سنگین کشاورزی برای آماده‌سازی زمین نیشکر بسته به شرایط مزرعه متفاوت و
506 از حداقل 10 تا حداکثر 16 تردد در سال متغیر است. برای کاهش انرژی، زمان و هزینه‌ها، استفاده از خاکورزی حفاظتی
507 و همچنین سامانه‌های ترافیکی کنترل شده ضروری است. اهداف این تحقیق توسعه، و ارزیابی یک ماشین خاکورزی عمیق
508 نواری ترکیبی مجهز به یک ابزار خاکورز عمیق دو سطح‌کار، شامل یک زیرشکن کج تیغه دوطرفه، یک زیرشکن بالهدار
509 به همراه مجموعه‌ای از دیسک‌ها بود. برای بهینه‌سازی زیرشکن کج تیغه دوطرفه، تاثیر زاویه حمله (7.5 و 15 درجه) و
510 طول تیغه (150 و 200 میلی متر) بر عملکرد ابزار مورد بررسی قرار گرفت. همچنین برای بهینه‌سازی زیرشکن بالهدار،
511 بال آن با طول‌های مختلف (0، 200، 250 و 300 میلی متر) مورد آزمایش قرار گرفت. در نهایت، عملکرد دستگاه خاکورز
512 عمیق نواری توسعه‌یافته با یک زیرشکن معمولی مورد استفاده برای خاکورزی عمیق در مزارع نیشکر مقایسه شد. نتایج
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514 150 میلی‌متر و زیرشکن بالهدار به طول 250 میلی‌متر مجهز شود. نتایج نشان داد که مقاومت ویژه ماشین توسعه یافته نسبت
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516 زیست برای تولید پایدار نیشکر در جنوب غربی ایران می‌باشد.

517