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Full length article

Performance evaluation of compost turning machine suitable for smallholding

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ABSTRACT

This study aims to develop and evaluate a small local machine to turn compost windrows for smallholdings. The experimental parameters were tested at three kinematic parameters (KPs) (15, 25, and 35), two blades shape (L-shape and I-shaped), four turning number times (every 7, 14, 21, 28 days), and two residues' mixtures (Rice straw + livestock manure and Cotton stalk + live-stock). The evaluation included compost density, maturity period, machine productivity, energy requirements, turning cost, and compost quality. The lowest compost density (398 kg/m³) and maturity period (10 weeks) were at kinematic parameter 35, turning every 7 days, and I blade for Rice straw compost. So, it is recommended to operate the machine at kinematic parameter 35, turning times every 7 days, and I blade to get the excellent compost specifications and reduce maturity time.

1. Introduction

The agricultural activities in Egypt generate about 46.7 Mg/year of agricultural residues, of which 52 % are unused and can be bio-converted to about 10 Mg of compost every year, which leads to an increase in Egypt's production of fertilizers by more than 60% (Elfeki et al., 2017). On the other hand, agricultural residue burning is considered an economic loss, has environmentally harmful effects (the black cloud), reduces the soil's microbial activities, and causes the growth of pests and pathogens that attack new crops (Nakhla et al., 2013). So, composting the agricultural residues reduces environmental pollution and recycles agricultural residues into precious products, such as organic fertilizers (Jiang-ming, 2017). Using organic fertilizer increases the soil's organic matter content, which gradually decreases over time (El-Maddah, 2000). Also, it improves water holding capacity, reduces foul odor, and destroys weed seeds and pathogens (Ghaly et al., 2006).

In the composting process, the microorganisms decompose agricultural residues in aerobic conditions and convert them to compost rich in plant nutrients and humus (Sharma et al., 2011). The main criteria for most compost production methods are C:N ratio from 25:1 to 30:1, water content from 50 to 60 %, temperature from 50 to 60 ^{0}C, pH from 6.5 to 8, and density of about 590 kg/m^3 (Horn, 1995; Rynk, 1992). The most common composting method involves stacking organic wastes into windrows that are turned periodically (Elfeki et al., 2017). Jiang-ming (2017) evaluated compost windrow has 1.5 wide, 1 m high, and 4.8 long with turning by machine and got an excellent compost quality in 63 days to maturity.

Regularly turning the compost windrow maintains the aerobic condition, making the compost uniform, and encouraging the thermophilic processes (Sarkar et al., 2016). The operator is exposed to harmful conditions during compost turning due to high ambient temperatures, awful smells, and released gases (Schedler et al., 2020). Also, the lack of labor cause delay in the turning process, which severely affects the final compost quality. So the compost turning machine is necessary to

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minimize maturity time, reduce toil and fatigue, and reduce overall costs (Imbabi, 2003). However, compost turning is still carried out manually in Egypt (Sayed et al., 2021); in addition, the compost turning machines (attached to a tractor or self-propelled) are usually imported and expensive (Baiomy, 2010). Resulting to there are almost no composting factories in rural areas except for the participation of farmers on an individual basis in composting organic matter (Elfeki et al., 2017).

Yousef (2001) used a fodder beet chopper to turn the compost under local conditions as a dual-purpose machine. Tai and He (2007) stated that the turnover frequency significantly shorted the composting operation time to 8 – 13 weeks. Also, Abdel – Mottaleb (2008) found that the composting time decreased to 14 weeks by mechanical turning. Sayed et al. (2021) found that reducing forward speed from 1.6 to 1 km/h at a turning drum speed of 250 rpm and three turning times per month reduced the period to maturity from 20 to 10 weeks for rice straw compost and from 24 to 14 weeks for Cotton stalks compost with the use of self-propelled turning machine. Also, increasing turning times from 1 to 4 turnings per month, at a forwarding speed of 1.4 km/h and turning drum speed of 250 rpm decreased the period to maturity from 24 to 11 weeks for rice straw and from 24 to 15 weeks for cotton stalks with the use of self-propelled CTM. Fouda (2009) showed that increasing the kinematic parameter from 25 to 45 decreased compost turning machine productivity from 2.75 to 2.1 m^3/h and compost density from 610 to 490 kg/m^3 under pile height 0.8 m. Also, Morad et al. (2008) showed that increasing the forward speed from 1.2 to 1.5 km/h at four times per month turning number and pile height of 1 m increased fuel consumption from 7.5 to 10 lit/h when using a small self-propelled turning machine. Also, increasing the machine's forward speed from 1.5 to 2 km/h increased the required power from 26.5 to 35 kW. Muzamil et al. (2013) found that optimum conditions for turning machine were straight-shaped blades at a rotor speed of 300 rpm with a forward speed of 2.26 km/h for a pile height of 1 m. and three turning times at a regular interval of 10 days resulted in a reduction in density from 514.3 to 299.1 kg/m^3.

Khater (2015) stated that different compost raw materials' physical and chemical properties were C/N ratio from 14.22:1 to 18.52:1, bulk density from 420 to 655 kg/m^3, and pH from 6.3 to 7.8. Radovich and Hue (2014) found that the ratio of carbon to nitrogen in compost is probably the best-known objective indicator of compost quality. The optimal C/N ratio is ranged from 10:1 to 20:1. Alfano et al. (2008) mentioned that the costs of turning operation involve transport of the raw materials to the experiment area, labor costs, and machines. Brodie et al. (2000) found that the cost of raw materials in the buying represented 60 to 70 % of the cost of producing compost. Ewida et al. (2009) calculated the total cost of turning operation as 130 LE./h, 7.2 LE./m^3.

The main objectives of this study were developing a local self-propelled harvesting machine as a dual-purpose machine to turn the compost for small farms and optimizing some operating parameters affecting the Compost turning machine performance.

2. Materials and methods

2.1. The raw materials

Crop residues (Rice straw and Cotton stalks) were used as raw materials; also, live-stock manure was added to accelerate the composting process. The plant residues were dried and chopped into small pits from 3 - 5 cm in length to facilitate decomposing residues mixed immediately with the live-stock manure by a ratio of 2:1 (by weight). The compost windrow was a trapezoidal shape of 4 m in length with a bottom width of 1.2 m, top width of 0.5 m, and 0.9 m in height. Water spraying adjusted the initial moisture content to approximately 55 – 60 %. During the operation, the un-decomposable materials like plastic and bottles were removed manually to reduce the hindrance in the subsequent processes.

2.2. The compost turning machine

The turning machine used in experiments (Fig. 1) was developed from a self-propelled harvesting machine with modified attachments that suit compost turning with low cost and are suitable for smallholdings. That adds economic value to the harvesting machine by adding another operation (compost turning). The machine manufacturing country is Italy Model GK-3 with a diesel engine of 15 hp (11.5 kW). The main components of the machine are a mainframe, diesel engine, three wheels, a turning shaft with blades, a pair of ball bearings, and a water tank with a secondary stand. The overall dimensions were 304 cm in length, 147 cm in width, and 180 cm in Hight. The agitation device (rotor shaft) was manufactured from medium carbon steel, 160 cm in length and 4 cm in diameter. The rotor shaft holds seven blade sets; each set has four blades made from medium carbon steel. The distance between every two blade sets is 13.75 cm. Two types of blades were used in the experiments, one of them is L shape, and the other is I shape. The share of I shape made 45^o angle with the horizontal section of the rotor shaft while the share of L shape made 0^o angle (Fig. 2). The secondary frame carries a cylindrical water tank made of galvanized iron anti-corrosion with 60 cm diameter, 105 cm length, and 0.3 m^3 capacity to add water during turning operation. The water tank has a faucet that pours into a hose 1 meter long with nine holes. The maximum discharge of all holes is 1.5 m^3/h.

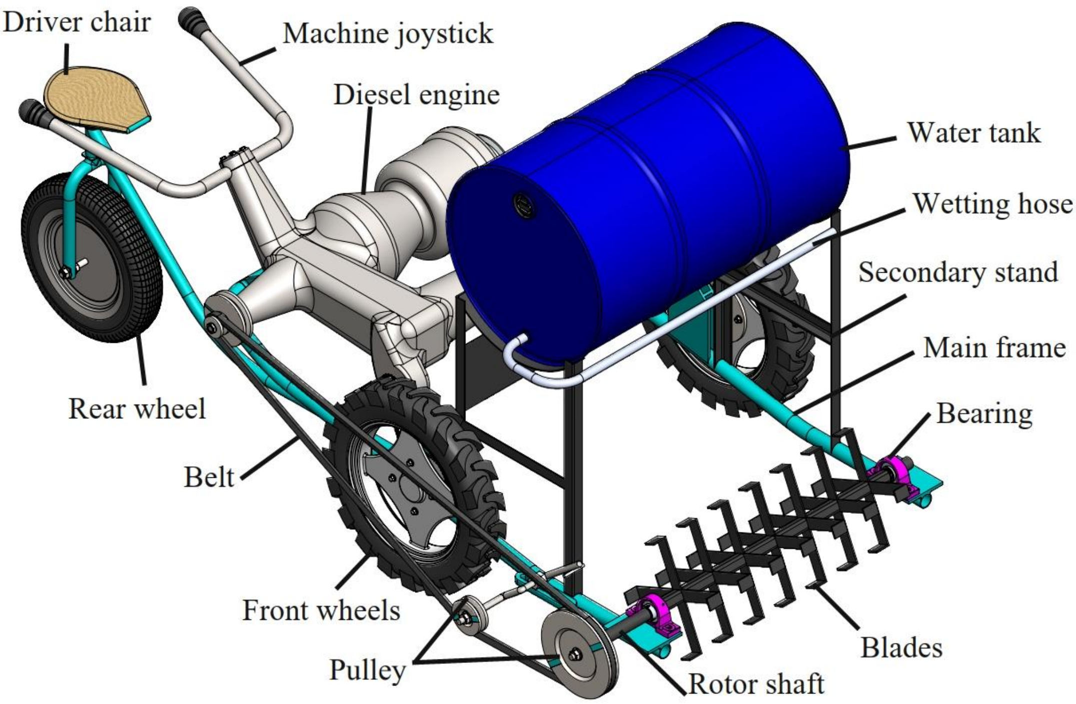
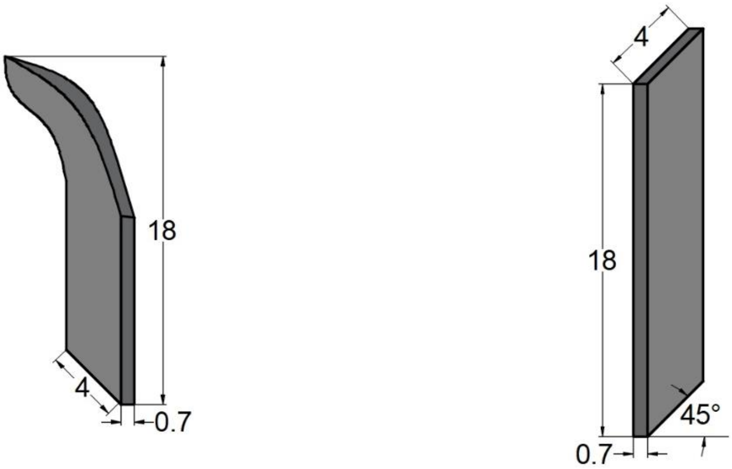


Fig. 1. The components of the compost turning machine.



(a): The L shape blade. (b): The I shape blade.

Fig. 2. The two types of turning blades (Dim. in cm).

2.3. *Experimental procedures*

The experiments were conducted under rotor peripheral velocity of 540 rpm and three forward speeds of 1.18, 1.65, and 2.76 km/h, which represented three kinematic parameters (KPs) value 15, 25, and 35, two-blade shapes (L-shape and I-shaped), two residues mixtures (Rice straw + live-stock manure and Cotton stalk + live-stock), and four turning times every 7, 14, 21, 28 days were tested. The turning machine performance was evaluated in compost density, maturity period, machine productivity, energy requirements, machine operation cost, and the end compost quality.

2.4. *Measurements*

Compost density

It is a ratio of the material's mass per unit volume. Compost density was determined according to the following formula (Sayed et al., 2021):

$$\rho = \frac{M}{V} \quad [1]$$

where:

ρ = Compost density, kg/m^3.

M = Compost sample mass, kg.

V = Compost sample volume, m^3.

Maturity period

The required time for compost maturity was recorded for all treatments from the beginning of operation until compost maturity.

The compost turning machine productivity

The turning machine productivity (m^3/h) was calculated as the following equation (Fouda, 2009):

$$M.C. = A \times S \times \eta_M \quad [2]$$

where:

M.C. = Actual machine productivity, m^3/h.
A = Operational cross-sectional area, m^2.
S = Machine forward speed, m/h.
η_M = Machine efficiency, %.

The machine efficiency was calculated based upon the total adequate operation time function of losing time during operation (Kepner et al., 1978).

Turning power

The turning power can be determined as given by (Barger et al., 1963):

$$T.P. = F_c \times C.V. \times \eta_{th} \times 427 \times \frac{1}{75} \times \frac{1}{1.36} \quad [3]$$

where:

T.P. = Turning power, kW.
C.V. = Calorific value of fuel, kcal/kg (C.V. = 10000 kcal/kg).
427 = Thermomechanical equivalent, kg.m/kcal.
η_{th} = Thermal efficiency of the engine, % (η_{th} = 30 % for diesel engine).

Energy requirements

The energy requirements were calculated as the following equation (Fouda, 2009):

$$E.R. = \frac{T.P.}{M.C. \times \rho} \times \text{Turning number to maturity} \quad [4]$$

$$E.R.V. = \frac{T.P.}{A.M.P.} \quad [5]$$

where:

E.R. = Energy requirements, kW.h/Mg.

Turning cost

The following relationship was developed by (Awady, 1978) to estimate the hourly cost of machine operation:

$$C = \frac{P}{h}\left(\frac{1}{e} + \frac{i}{2} + t + r\right) + (0.9\,hp + f + s) + \frac{w}{144} \quad [6]$$

where:

C = Cost per hour of operation, LE./h.
P = Capital machine price, LE.
h = Yearly working hours of the machine, h/year.
e = Life expectancy of the machine, year.
i = Annual interest rate, %.
t = Annual taxes and overheads ratio, %.
r = Annual repairs ratio of the total investment, %.
hp = Horsepower of the engine, hp.
f = Specific fuel consumption, lit/hp. h.
s = Price of fuel, LE. /lit.
w = Labor wage rate per month, LE. /month.
= The operator's monthly average working hours, h.

The total cost per m^3 of the experimented machine was calculated as the following:

$$T.C. (LE./m^3) = \frac{C}{A.M.P.} \quad [7]$$

where:

T.C. = Total cost of m^3, LE. /m^3.

$$T.C. (LE./Mg) = \frac{T.C. (LE./m^3)}{\rho} \times \text{Turning number to maturity} \quad [8]$$

The finished compost quality

The chemical and physical properties of final compost were analyzed in the National Center for Agricultural Research laboratory. The compost quality assessment includes the C/N ratio, Organic material percentage (%), and water holding capacity (g water / g dry).

3. Results and discussions

Effect of the kinematic parameter (KP) on compost density

From Fig. 3, the compost density decreased with increasing KP from 15 to 35 with different blade shapes and crop residues. Results showed that the lowest compost density was 398 kg/m^3 at kinematic parameter 35, turning every 7 days, and I blade for Rice straw mixture compost. Increasing the kinematic parameter from 15 to 35 decreased compost density from 451 to 398 kg/m^3 at turning every 7 days, and I blade for Rice straw mixture compost. The lowering of density is attributed to decreasing the forward speed relative to the rotational speed, which leads to increased mixing and shredding of compost windrow and the distribution of the microorganisms on all materials and facilitates the decomposition of residues.

The compost density decreased by 32 % and 34 % for Rice straw, and Cotton stalks compost, respectively, when the turning times dropped from 28 days to 7 days at kinematic parameter 35 and I blade. The reasons were increasing the released amount of water vapor and carbon dioxide from the windrow and increasing the number of turning and mixing times for raw materials. Also, compost density decreased using I blade compared with L blade in Rice straw, and Cotton stalks compost.

The compost density was 398 kg/m³ using the I blade, while it was 427 kg/m³ using the L blade for Rice straw compost at kinematic parameter 35 and turning times every 7 days. For the Cotton stalks compost, the compost density was 408 kg/m³ using the I blade, while it was 450 kg/m³ using the L blade at KP 35 and turning times every 7 days.

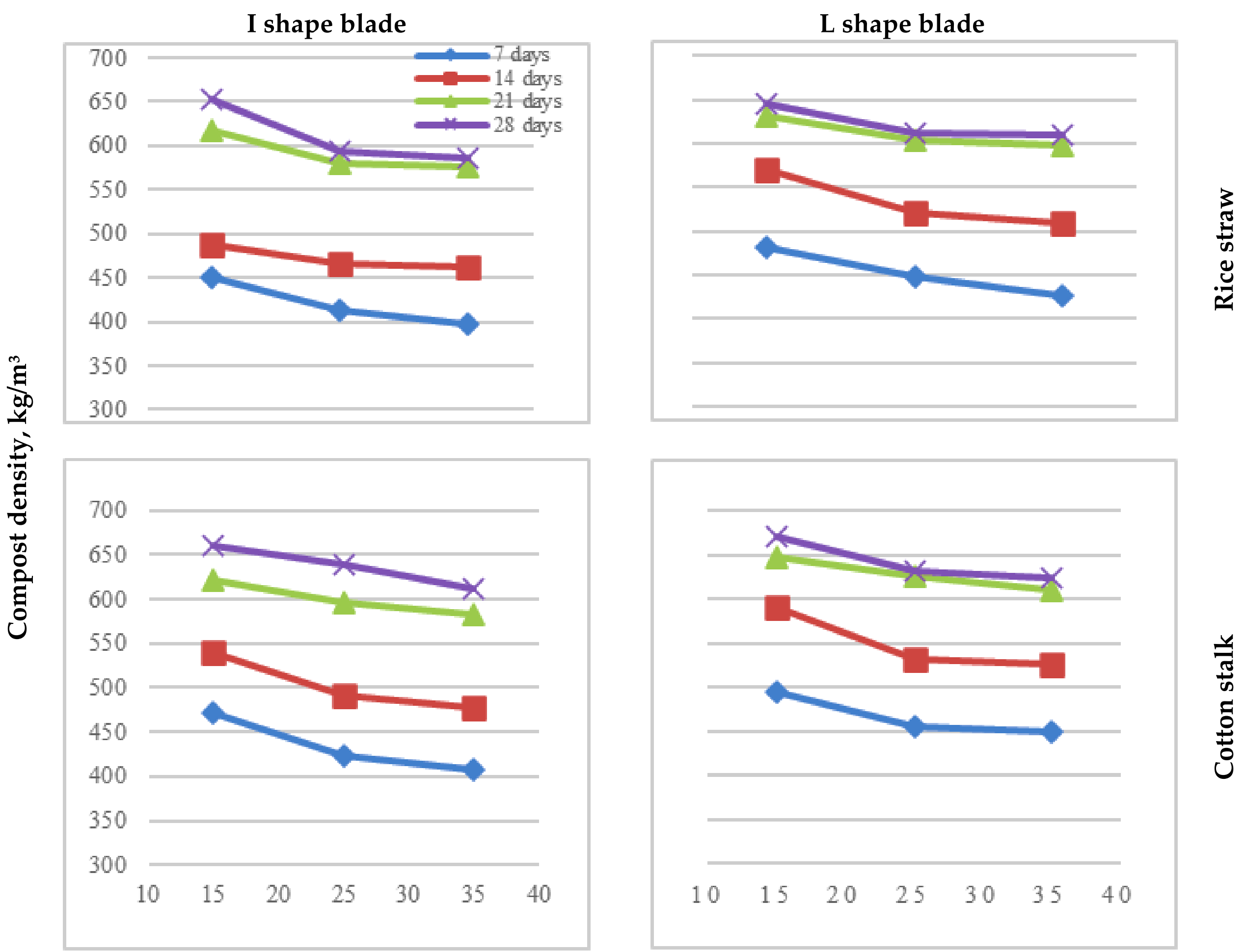


Fig. 3. Effect of kinematic parameter value on compost density under two different types of residues and blades.

Effect of the kinematic parameter (KP) on maturity period

The KP value negatively affected the compost maturity period (Fig. 4), where increasing the KP value decreased the maturity period in most treatments. The lowest period to compost maturity was 10 and 13 weeks for Rice straw and Cotton stalks compost, respectively, at KP 35, turning every 7 days, and I blade.

Increasing KP from 15 to 35 decreased compost maturity time from 12 to 10 weeks at turning every 7 days, and I blade for Rice straw compost. The lowering of the maturity period is attributed to decreasing the forward speed relative to the rotational speed, which leads to mixing of the compost windrow materials and good distribution of the microorganisms on all materials, which facilitates the residues decomposition and short the time.

The maturity period decreased with increasing the number of turning times. The maturity time decreased from 14 to 10 and 18 to 12 weeks for Rice straw and Cotton stalks compost, respectively, when the number of turning reduced from every 28 days to every 7 days at KP 35 and I blade. The effect of blade shape was a maturity period of 10 weeks for the I blade and 12 weeks for the L blade at KP 35, turning time every 7 days, and Rice straw compost. While maturity period was 12 weeks for the I blade and 13 weeks for the L blade at KP 35, turning every 7 days, and Cotton stalks compost.

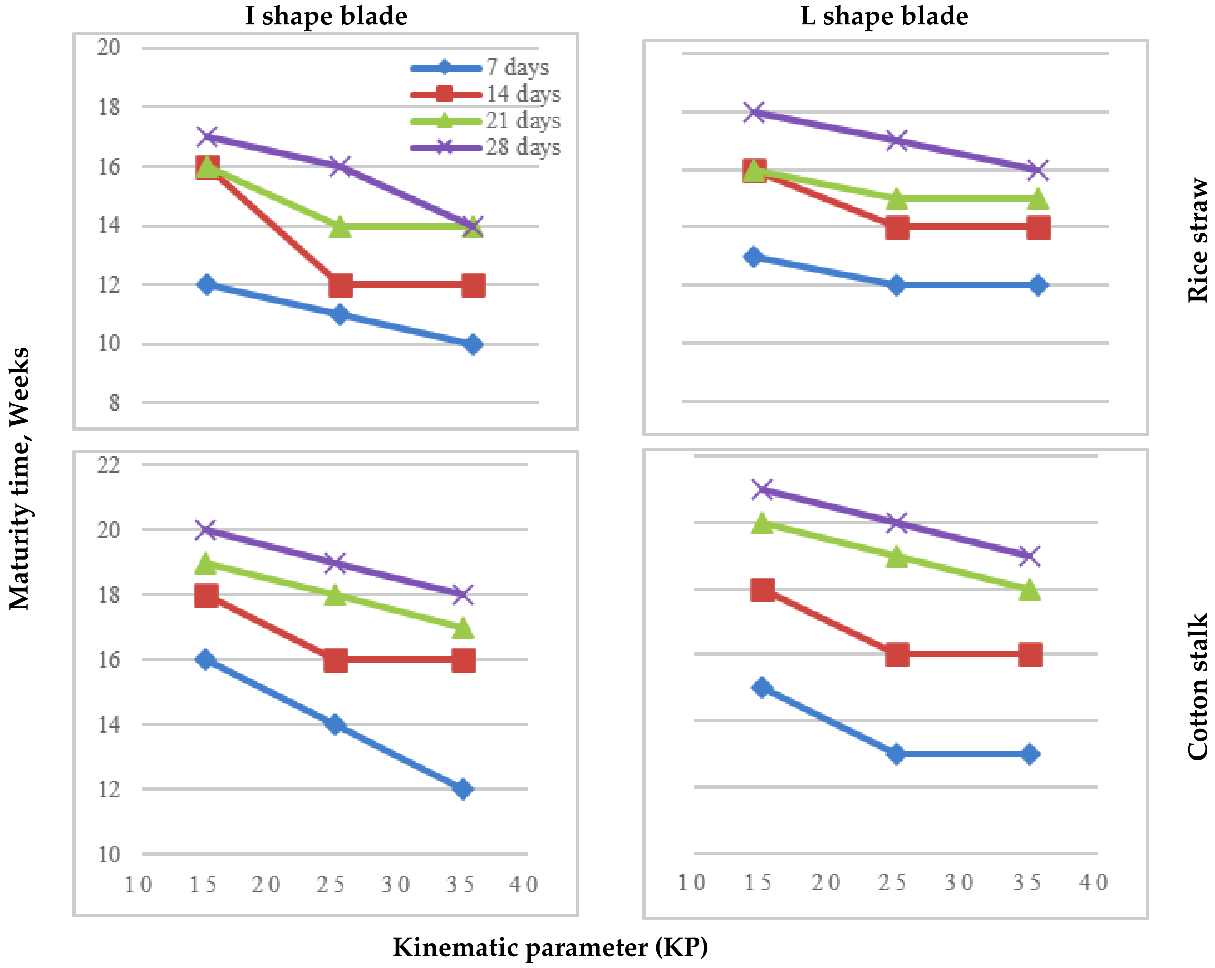


Fig. 4: Effect of kinematic parameter value on period to maturity under two different types of residues and blades.

Effect of the kinematic parameter (KP) on compost turning machine (CTM) productivity

Fig. 5 shows that the CTM productivity increased by decreasing the kinematic parameter due to increasing the CTM forward speed. The reduction of KP from 35 to 15 increased CTM productivity from 790 to 1680 and 810 to 1821 m^3/h with the I blade and L blade, respectively. The effect of blades type appeared by increasing productivity with the L blade compared with the I blade. This is attributed to the operating width of the I blade being more than the L blade, which increases the machine's resistance during progress and reduces productivity.

Effect of the kinematic parameter (KP) on energy requirements

The energy requirements are a function of both fuel consumption and machine productivity. In Fig. 6, we notice increasing energy requirements from 203 to 292 and 180 to 240 W.h/Mg for I, and L blades, respectively, when the KP rose from 15 to 35. The lowest energy requirements were 203 and 180 W.h/Mg for the I and L blade, respectively, while the highest energy requirements were 292 and 240 W.h/Mg for the I and L blade, respectively.

Effect of the kinematic parameter (KP) on turning cost

The turning cost is essential to evaluate CTM performance. The turning cost increased from 3 to 6.5 and 2.8 to 6.3 LE./m^3 for I and L blade respectively, when the KP increased from 15 to 35, as shown in Fig. 7.

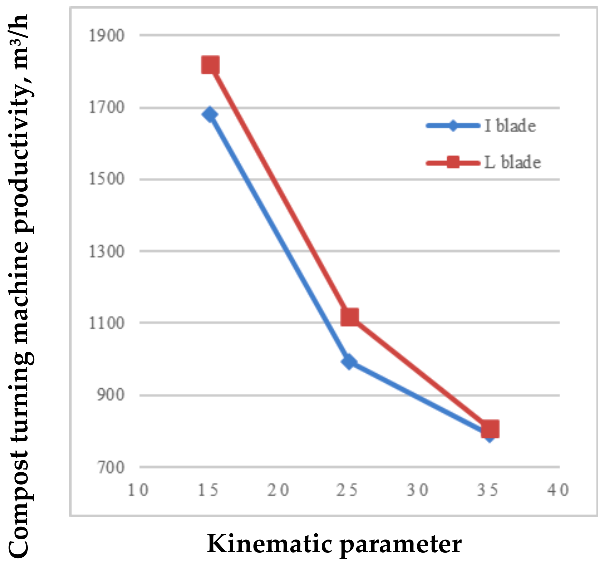


Fig. 5. Effect of kinematic parameter value on CTM productivity under two different types of blades.

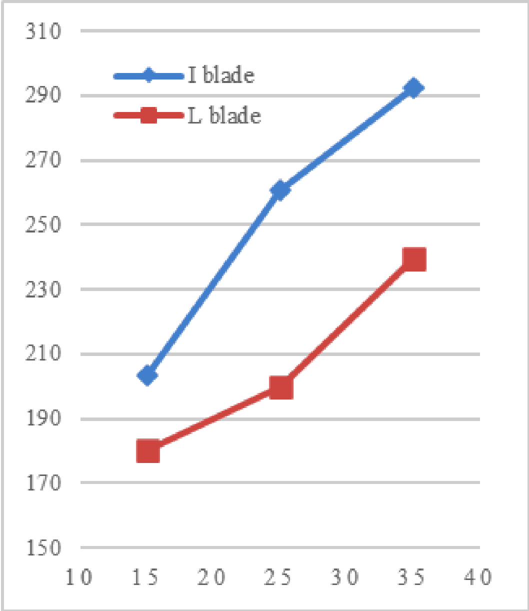


Fig. 6: Effect of KP value on Energy requirements under two different types of blades.

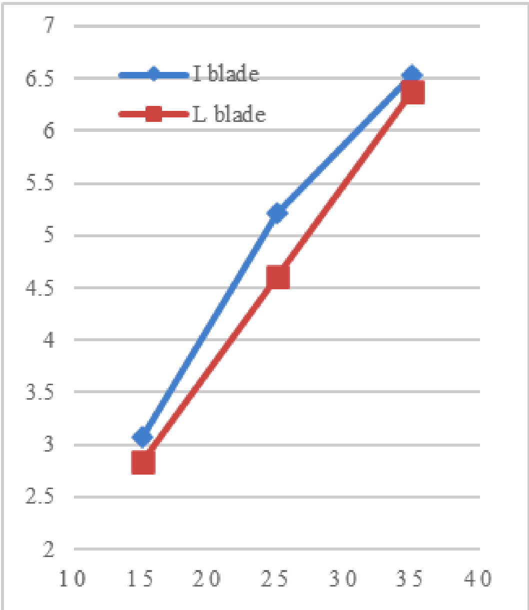


Fig. 7. Effect of KP value on turning cost under two different types of blades.

Final compost quality

The analysis of matured compost for Rice straw and Cotton stalks compost appears in Table 1 compared with the ideal compost specifications (Khater, 2012).

4. Conclusions

The developed CTM can be used on small farms and is highly efficient with low cost. The lowest compost density was 398 kg/m^3 and the most down maturity period was 10 weeks at KP 35, turning every 7 days, and I blade for Rice compost. The machine also achieved the highest productivity (1821 m^3/h), lowest energy requirements (180 W.h/Mg), and lowest costs (2.8 LE./Mg) at KP 15, turning every 7 days, and L blade. The recommended operation parameters for CTM are KP 35, turning times every 7 days, and I blade to get the excellent compost specification and reduce maturity time.

Table 1
The Rice staw and Cotton stalks final compost analysis

	Ideal range	Rice straw compost	Cotton stalks compost
C/N ratio	14:1 - 18.5:1	15.3:1	17.4:1
Organic materials, %	28.6 - 41.2	35	33.1
Water holding capacity, g water/ g dry	3.5 - 4.4	4.1	3.9

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تقييم آداء آلة تقليب كمبوست تناسب الحيازات الصغيرة

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الملخص العربي

تهدف هذه الدراسة إلى تطوير وتقييم آلة محلية صغيرة ذاتية الحركة تستخدم لتقليب السماد العضوي المصنع (الكمبوست) في مصفوفات بحيث تكون مناسبة للحيازات الصغيرة. تم اختبار الآلة تحت ثلاث معاملات كيناماتيكية (١٥ ، ٢٥ ، ٣٥) ، ونوعين من الأسلحة الدورانية (شكل حرف L و شكل حرف I) وأربع فترات تقليب (كل ٧ ، ١٤، ٢١، ٢٨يوماً)، واثنان من مخاليط المخلفات الزراعية (قش الأرز المفروم مع مخلفات حيوانية وحطب قطن مفرومة مع مخلفات حيوانية).

ولتقييم الآلة والكمبوست الناتج تم قياس العناصر التالية:

١) كثافة السماد.
٢) فترة النضج.
٣) إنتاجية الآلة.
٤) متطلبات الطاقة.
٥) التكاليف.
٦) جودة الكمبوست النهائي.

وكانت أهم النتائج المتحصل عليها كما يلي:

كانت أقل كثافة للكمبوست هي ٣٩٨ كجم / م٣ وأقل فترة نضج هي ١٠ أسابيع عندما كان المعامل الكيناماتيكي يساوى ٣٥ مع التقليب كل ٧ أيام باستخدام السلاح على شكل حرف I وذلك للكمبوست المصنوع من قش الأرز.

لذا يوصى باستخدام الآلة المطورة مع المتغيرات السابقة للحصول على جودة كمبوست عالية مع تقليل فترة النضج.