UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A TRACTOR-MOUNTED KENAF HARVESTING MACHINE

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By

DAUDA SOLOMON MUSA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

March 2014

DEDICATION

This thesis is dedicated to the glory of God

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Doctor of Philosophy

DEVELOPMENT OF A TRACTOR-MOUNTED KENAF HARVESTING MACHINE

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March 2014

Chairman: Professor Ir. Desa Bin Ahmad, PhD, P.Eng.
Faculty: Engineering

The potential of kenaf (Hibiscus cannabinus L.) as an industrial commercial crop has been exploited in recent times. Kenaf harvesting operations are manually done or use other machinery for sugarcane. This makes harvesting difficult, time consuming and high labour cost and demand. A survey of kenaf harvesting machinery revealed that sugar cane harvesters and other machinery were either modified or adopted to harvest kenaf, hence field equipment for harvesting whole kenaf stems continues to be of interest in kenaf production. This necessitated the need to develop an efficient kenaf harvesting machine. This study focused on the development of a tractor-mounted kenaf harvesting machine to harvest whole kenaf stems which is either broadcast or row-planted. In this regard a study on the physical and cutting characteristics of kenaf stem varieties FH 952 and V 36 revealed that the maximum plant height recorded was 310 cm and the lowest was 150 cm. Maximum stem diameter was 30 mm and the smallest was 14 mm. The moisture contents determined ranged between 73-75% (wet basis) for V 36 at harvest and 60.3-62.3% (wet basis) for FH 952. The cutting characteristics of kenaf stems at three different moisture content levels of 35%, 55% and 72% were also studied. The results revealed that the maximum cutting force and shearing energy were 1584.55 N and 8.75 J, respectively for 35% moisture content, while 694.86 N and 3.50 J were recorded for 72% moisture content. The Young's modulus ranged between 67.59 MPa to 234.24 MPa. Laboratory experiments were conducted on cutting kenaf stem of variety V36 using a rotary serrated cutting system. The effects of cutting speeds on the cutting torque and cutting power of varying kenaf stem diameters and at different moisture contents and four different cutting speeds, 400 rpm, 500 rpm, 600 rpm and 700 rpm were investigated. Based on the experiments, the cutting speed had significant effect on the cutting power and torque. The cutting speed was directly proportional to the specific cutting power, while the cutting torque was inversely proportional to the moisture content. Increasing the rotational speed from 400 rpm to 700 rpm reduced the cutting torque from 1.91 Nm to 1.49 Nm. The cutting torque was observed to be higher at lower moisture levels of less than 35%. As the moisture content increased to values greater than 35%, the torque decreased considerably. This indicates that an increase in moisture content reduces cutting torque as shown by the model coefficient of moisture content, $ct = 1.771 - 0.02mc$. This means more energy savings and high efficiency would be achieved at high cutting speeds as compared to impact cutting system at similar speeds. Regression equations capable of predicting

cutting torque and cutting power at varying stem diameters and cutting speeds, in relation to kenaf stem moisture contents are presented. After the aforementioned studies, a kenaf harvesting machine incorporating a rotary serrated cutting system was developed and its performance evaluated based on the physical and cutting properties studied. The kenaf harvester is tractor-mounted and comprises of a hydraulic, cutting and gathering systems. The parameters evaluated were the harvesting field efficiency (FE), effective field capacity (EFC) and machine material capacity (MC). Kenaf varieties V36 and FH 952 were used for the experiments to determine the performance of the machine. Different tractor speeds ranging from 2.0 to 7.7 km hr^{-1} were used. Field test results of the machine harvesting kenaf varieties V36 and FH 952 gave a harvesting field efficiency of 61 – 76%, effective field capacity of 1.19 – 3.68 ha/day and machine material capacity of 91.8 – 283.66 tons/day. The optimal operating forward speed at 3.7 km hr^{-1} achieved an efficiency of 76%. Results of the field test showed that the tractor speed had a significant effect on the performance of the machine, in terms of its effective field capacity, field efficiency and the machine material capacity. The machine performance revealed a satisfactory performance of the cutting system and it is suitable for harvesting kenaf stems of varying sizes. Total operational cost of the developed kenaf harvesting machine of RM 322,870.40/annum was compared with the common manual harvesting method of RM 13,500,000/annum widely practiced in Malaysia, and also the 4-row impact cutting kenaf harvesting machine of RM 416,636.00. The analysis showed that about RM13,177,129.60/annum will be saved when compared with the manual method and a saving of RM 93,765.60/annum when compared with the 4-row impact cutting kenaf harvesting machine.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah.

PEMBANGUNAN MESIN PENUAI KENAF YANG DIPASANG PADA TRAKTOR

Oleh

DAUDA SOLOMON MUSA

Mac 2014

Pengerusi: Profesor Ir. Desa Bin Ahmad, Ph.D, P.Eng.
Fakulti: Kejuruteraan

Potensi kenaf (Hibiscus cannabinus L.) sebagai tanaman industri komersial telah dipergunakan sepenuhnya akhir-akhir ini.. Penemuan baru berasaskan kajian di ladang menarik minat ke arah pembangunan sebuah mesin penuai kenaf yang efisien. Minat tersebut berterusan untuk menghasilkan mesin yang boleh menuai batang kenaf yang panjang dalam sektor pengeluaran tanaman tersebut. Kajian ini memfokus kepada pengubahsuaian dan penambahbaikan jentera penuai kenaf agar dapat memotong batang kenaf yang panjang samaada ditanam secara tebar atau secara berbaris. Kajian terhadap ciri batang kenaf jenis FH 952 dan V 36 menunjukkan bahawa ketinggian maksimum yang direkodkan adalah 310 cm manakala ukuran terendah adalah 150 cm. Garispusat maksimum batang adalah 30 mm manakala ukuran minimum adalah 14 mm. Kandungan kelembapan semasa penuaian adalah di antara 73-75% (asas basah) bagi kenaf jenis V 36 dan antara 60.3-62.3% (asas basah) bagi kenaf jenis FH 952. Ciri pemotongan batang kenaf pada tiga kandungan kelembapan antara 35%, 55% dan 72% telah dikaji. Keputusan kajian menunjukkan daya pemotongan maksimum dan tenaga ricihan adalah 1584.55 N dan 8.75 J masing masing pada kandungan kelembapan 35% manakala pada kandunagn kelembapan 72% daya pemotongan maksimum dan tenaga ricihan adalah nasing masing 694.86 N dan 3.50 J. Nilai Young's modulus adalah diantara 67.59 MPa dan 234.24 MPa. Ekperimen pemotongan batang kenaf jenis V 36 telah dilakukan di dalam makmal menggunakan sistem pemotongan bilah bergerigi yang berputar. Kesan kelajuan keatas daya kilasan dan kuasa bagi batang kenaf pelbagai garispusat dan kandungan kelembapan berbeza telah dikaji pada empat kelajuan berbeza antara 400, 500, 600 dan 700 psm. Berdasarkan ekperimen tersebut, kelajuan pemotongan memberikan kesan bererti ke atas kuasa pemotongan dan kilasanKelajuan pemotongan berkadaran terus dengan kuasa pemotongan tentu manakala kuasa kilasan pemotongan berkadaran songsang dengan kandungan kelembapan. Peningkatan kelajuan putaran dari 400 psm kepada 700 psm mengurangkan daya kilasan pemotongan dari 1.91 Nm kepada 1.49 Nm. Daya kilasan pemotongan didapati tinggi pada tahap kandungan kelembapan yang rendah di bawah paras 35%. Peningkatan kandungan kelembapan melebihi 35% akan mengurangkan daya kilasan secara mendadak. Ini jelas menunjukkan bahawa peningkatan kandungan kelembapan akan mengurangkan daya kilasan pemotongan sebagaimana yang ditunjukkan oleh pekali model kandungan kelembapan, ct = 1.771-0.02mc. Ini bererti

lebih banyak penjimatan tenaga dan prestasi lebih tinggi dapat dicapai pada kelajuan pemotongan yang tinggi berbanding sistem pemotongan cara hentaman pada kelajuan pemotongan yang sama. Hasil Persamaan Regresi yang mampu meramal daya kilasan dan kuasa pemotongan bagi pelbagai garispusat batang kenaf dan kelajuan pemotongan pada kandungan kelembapan berbeza turut dipaparkan. Lanjutan dari kajian makmal sebuah mesin penuai kenaf telah dibangunkan menggunakan sistem pemotongan putar dengan bilah bergerigi dan dinilai prestasinya berdasarkan ciri-ciri fizikal dan mekanikal yang dikaji terlebih dahulu.. Penuai kenaf tersebut disangkut pada traktor dengan sistem pemotongan dan pengumpulan berasaskan kuasa hidraul. Parameter yang dinilai adalah kecekapan penuaian ladang (FE), keupayaan ladang berkesan (EFC) dan keupayaan bahan mesin (MC). Kenaf jenis V 36 dan FH 952 telah digunakan dalam ekperimen untuk menentukan prestasi mesin tersebut menerusi kelajuan traktor yang berbeza antara 2.0 ke 7.7 km/jam. Keputusan ujian mesin di ladang kenaf jenis V36 dan FH 952 menghasilkan kecekapan penuaian ladang antara 61-76%, keupayaan ladang berkesan antara 1.19-3.68 ha/hari dan keupayaan bahan mesin antara 91.8 hingga 283.66 tan/hari. Pergerakan kehadapan pada kelajuan optimum 3.7 km/jam menghasilkan kecekapan 76%. Keputusan ujian di ladang menunjukkan bahawa kelajuan traktor memberi kesan bererti ke atas prestasi mesin dari aspek keupayaan ladang berkesan, kecekapan ladang dan keupayaan bahan mesin. Prestasi mesin menunjukkan pencapaian sistem pemotongan yang baik dan sesuai untuk penuaian batang kenaf pelbagai saiz. Jumlah kos operasi mesin yang dibangunkan sebanyak RM 322,870.40/tahun telah dibandingkan dengan kos operasi kaedah manual yang diamalkan di Malaysia sebanyak RM 13,500,00.00/tahun serta kos operasi sebanyak RM 416,636.00/tahun bagi mesin penuai jenis 4-baris yang menggunakan sistem pemotongan hentaman.. Hasil analisis menunjukkan bahawa mesin yang dibangunkan dapat menjimatkan kos sebanyak RM13,177,129.00/tahun jika dibandingkan dengan kaedah manual dan penjimatan kos sebanyak RM 93,765.60/tahun jika dibandingkan dengan mesin penuai jenis 4-baris yang menggunakan sistem pemotongan hentaman.

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I certify that a Thesis Examination Committee has met on 6 March 2014 to conduct the final examination of Dauda Solomon Musa on his thesis entitled "Development of a Tractor-Mounted Kenaf Harvesting Machine" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date:

DECLARATION

Declaration by the student

I hereby confirm that:

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Declaration by Members of Supervisory committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as slated in Rule 41 in Rules 2003 (Revision 2012-2013) were adhered to.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANE	Knife Edge Angle
ANOVA	Analysis of Variance
ANR	Knife Rake Angle
ASABE	American Society of Agricultural and Biological Engineers
CFC	Common Fund for Commodities
DMRT	Duncan's Multiple Range Test
EFC	Effective Field Capacity
FE	Field Efficiency
IJSG	International Jute Study Group
INTROP	Institute of Forestry and Forest Products
LFRT	Long Fiber Reinforced Thermoplastic
LKTN	Lembaga Kenaf Dan Tembakau Negara (Bahasa Melayu)
MARDI	Malaysian Agricultural Research and Development Institute
MC	Material Capacity
PTO	Power Take Off
RM	Malaysian Ringgit
SPSS	Statistical Package for the Social Sciences
TASH	Tractor-Attached Sugarcane Harvester
TFC	Theoretical Field Efficiency
TPU	Taman Pertanian University (Bahasa Melayu)
TSI	Taxes, Shelter and Insurance
UPM	Universiti Putra Malaysia
UNIDO	United Nations Industrial Development Organization
ϕ_{rk}	Rake angle
ϕ_{bk}	Bevel angle
ϕ_{ck}	Clearance angle
ϕ_{chk}	Chip angle
ϕ_{ok}	Oblique angle
ϕ_{cl}	Clip angle
r_{ek}	Edge radius
v_{km}	Knife velocity component
v_f	Mower's forward speed
v_{kg}	Knife velocity

CHAPTER 1

INTRODUCTION

1.1 Overview of Kenaf Harvesting

Kenaf (*Hibiscus cannabinus*) is an annual crop which is high in fiber yield (Bakhtiari et al., 2011; Mazumder et al., 2005). It is a third crop grown in the third world countries after bamboo and wood; while it is introduced as a source of renewable industrial crop in the developed countries. It is an annual warm season fiber plant which can thrive in both temperate and tropical regions (Abdul Khalil et al., 2010). Kenaf's ability to fix CO_2 has expanded its global consciousness as a natural source of cellulose fiber (Hossain et al., 2011; Lam et al., 2003). Its carbon dioxide assimilation capability, water purification ability and fast growing characteristics have invigorated several nations to consider kenaf as an alternative source of natural fiber (Kobayashi et al., 2003). Scordia et al., (2013) reported recent studies from Italy and Greece that even though kenaf is less efficient in using CO_2, water, solar radiation, and nitrogen than other carbon fixation (C_4) crops, but its assimilation rates are high. Thus, the utilization of kenaf as an alternative raw material choice to wood will aid in reducing deforestation, and subsequently increasing environmental stabilities.

The two constituents of kenaf stems are the outer bast fiber situated in the bark and the inner core fibers situated in the interior part of the stems (Ghahraei et al., 2011; Kemble et al., 2002; Mazumder et al., 2005; Paridah et al., 2011). The inner core constitutes about 60 to 75%, which is used in the production of low quality pulp, while the bast constitutes about 25 to 40%, which is used in the production of high quality pulp (Abdul Khalil et al., 2010; Xu et al., 2013). However, kenaf is well being discovered as a valuable raw material for making paper in developing nations (Kaldor et al., 1990). Kenaf fibers can be blended with synthetic fibers for carpet making. The fiber can also be used traditionally for making coarse bags, ropes, nets etc. (Lips and Dam, 2013; Saha et al., 2010). Kenaf industrially is applied in; automobile (Davoodi et al., 2010; Lips and Dam, 2013), aerospace, agriculture, construction, chemical process and packaging. Apparel fabrics and plastic/fiber composites from the fiber are its major end use products. Other end use products include; oil and chemical absorbents, animal bedding and horticulture potting mix from the core; and livestock feed from the leaf (Jonathan and Frank, 2010).

Kenaf stems are harvested when they are fully matured; this is generally done after the rainy season. To obtain a better fiber quality, the best harvest time is 20 days after the plant is in full blossom (Ghahraei et al., 2011). With the rising labour costs, profitable production of kenaf will rely on engineering machinery technology for effective production and management once kenaf come to be an industrial fiber crop. Forage harvesters are usually employed in harvesting kenaf stems, but these machines cuts the harvested stems into smaller pieces (Kobayashi et al., 2003). Conceptualization for the development of kenaf whole stem harvesters is adopted in two main forms; sugarcane harvester and forage harvester approaches. In both approaches, researchers and

industries have become resolute in adapting equipment that is in existence rather than concentrating in developing totally specific equipment for kenaf harvesting (Webber and Bledsoe, 2002). Therefore kenaf harvesting technology has become a matter of important interest.

The modification of a small sugarcane harvester to harvest kenaf stems was reported by Kobayashi et al., (2003). This harvester was able to harvest kenaf stems without cutting the stems into smaller pieces. Similarly, Webber III et al., (2002) also reported the use of sugarcane harvesters, with or without modification, to harvest kenaf stems, but the drawbacks of these harvesters taking into account are the transport and storage of the harvested materials. After the stems are allowed to dry on the field, they are then picked into wagons with machines incorporated with claws by gripping and loading them. This type of system is used to harvest both fresh and dried kenaf stems, but the performance of such equipment is not efficient. New Holland square baler model 575 was also employed to bale kenaf fibers but problems arose in its feeding section resulting in less feeding of the baler with enough fiber supplies. As a result, irregular bales were formed (Kemble et al., 2002).

A 4-row kenaf harvesting machine to cut whole kenaf stems was successfully designed, developed, and evaluated in UPM, Malaysia. The four-row harvester is a tractor drawn type comprising of impact cutting and the gathering units (Ghahraei, 2011). This harvester is limited to harvest kenaf stems planted in rows. Hence a harvester that can harvest both row and broadcast planted kenaf is necessary to accomplish these tasks.

1.2 Problem Statement

Kenaf harvesting operations are manually done or use other machinery for sugarcane. This makes harvesting difficult, time consuming and high labour cost and demand. Several field machinery have been identified for land preparation, sowing, weeding, fertilizer application and crop maintenance; however, specific machines are required for seed production and harvesting of kenaf (Akhir et al., 2005). A survey of kenaf harvesting machinery revealed that sugar cane harvesters and other machinery were either modified or adopted to harvest kenaf. The sugarcane harvesters did not perform efficiently and results in cut stems which are shorter in fragments. Besides the harvesting costs of a sugar cane harvesters and field choppers were expensive. Other kenaf harvesting machine developed in Universiiti Putra Malaysia is limited to harvesting crops planted in rows. Therefore, there is the need of developing a concept to come up with an economically viable machine. This machine should be capable of harvesting broadcast/row planted whole kenaf stems. It is also envisaged that this machine should be efficient enough to reduce high manual labour demand and allows for maximum field utilization. Hence, this study will attempt to develop, fabricate and evaluate the performance of this machine.

1.3 Contribution

The main contribution of this research is the development of a tractor-mounted kenaf harvesting machine that can harvest both row and broadcast planted crops. It will also tend to reduce energy consumption, maximize the usage of available cropping land by broadcast planting of kenaf seeds to avoid wastage of manpower and resources. This research will as well contribute to the literature in similar works on development of kenaf harvesting and forage harvesting related machines. Conference papers and journal articles published from this research will be made available to researchers as background knowledge. It is expected that this machine will successfully ease harvesting problems related to kenaf stems; invariably assisting in reducing manual labour demand.

1.4 Objectives

The main objective of this study was to develop, and test a new tractor-mounted broadcast/row planted kenaf harvesting machine. The specific objectives of this research are itemized below:

1. To determine kenaf stem physical and cutting properties in relation to the newly developed machine.
2. To determine the effects of blade speed on the stem cutting torque and cutting power requirement.
3. To develop and test a broadcast/row planted kenaf harvesting machine incorporating rotary serrated cutting mechanism.
4. To evaluate the performance of the kenaf harvesting machine.
5. To determine the operational/economic cost of the new machine in comparison to manual and the existing Universiti Putra Malaysia four row impact cutting kenaf harvester.

1.5 Scope

This study focuses on the development and evaluation of a new broadcast/row planted kenaf harvesting machine with particular interest in having clear and smooth cut whole stem using a rotary serrated cutting blade assembly. Furthermore, preliminary data on kenaf stem physical properties such as plant height, stem diameter, stubble height, cutting quality will also be studied. Similarly, cutting properties such as cutting force, cutting energy and compressive stress of the kenaf stem will also be studied. Also, evaluation of the harvester as well as preliminary tests such as field capacity and material handling capacity will also be conducted. Best operating speeds will also be studied and recommended. Economic cost analysis will similarly be carried out to compare between manual and the existing impact cutting four row kenaf harvester.

1.6 Thesis Outline

The organization of the thesis are in the following order; Chapter One which gives the overview of the study subject kenaf harvesting machine and the objectives of the research. In Chapter Two, related literatures were reviewed in line with the main

objective of developing a kenaf harvesting machine which includes; agronomy of kenaf plant, cultivation practices, and machinery employed in harvesting etc. Chapter Three describes the detail of materials and methods used to achieve the main objective of the study. Chapter Four presents the results obtained from the research, while conclusion of the research findings and proposed suggestions for further research in the area of study are presented in Chapter Five.

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