LOW-QUALITY FLAX STRAW BIOMASS HARVESTING FOR SUBSEQUENT USE AS FUEL: A REVIEW

I. Dudarev[1*], **A. Khomych**[2]

[1]*Lutsk National Technical University, Lutsk, Ukraine*
[2]*Liubeshiv Technical College, Liubeshiv, Ukraine*

AGRICULTURAL MACHINES
ACM
СІЛЬСЬКОГОСПОДАРСЬКІ МАШИНИ

Key words:
flax harvesting,
flax biomass,
flax straw bale,
flax straw burning,
solid fuel

Article history:
Received 22.07.2022
Accepted 25.08.2022

****Corresponding author:***
i_dudarev@ukr.net

ABSTRACT

To generate various forms of energy, the plant biomass can be burned directly or after its conversion into carbonized solid fuel, liquid fuel, or gaseous fuel. The yield of plant, which is used as biomass sources, need to be achievable with minimal energy inputs for plant cultivation, planting, harvesting and transporting. Using biomass in original form is very complicated, because of high moisture content, irregular shape and sizes, and low bulk density. Therefore, before removal from the field the biomass densification into bales is conducted. Unfavorable conditions for flax growing, harvesting and dew-retting are the reason for the low-quality flax biomass production. This biomass cannot be processed for fiber or other purposes. Therefore, flax straws are burned in the fields or are used as fertilizer by plowing into the soil, which are not good solutions for the environment and subsequent cultivation operations. The limit values of quality properties of flax stem, flax straw and retted straw for their processing are summarized, which can be used to determine the suitability of flax straw biomass for processing or burning. Low-quality flax biomass is inexpensive, ecofriendly and renewable, it can be used as solid fuel for heating greenhouses or buildings located near the field where the flax is grown. Various techniques of fibre flax and oilseed flax harvesting are presented in the article. The technique of low-quality flax harvesting is recommended, which include flax pulling out or flax cutting, flax threshing, flax straw windrow forming, flax straw natural drying on the field in natural way, flax bale forming, flax bale transporting, flax bale burning. This harvesting technology can be used for low-quality fibre flax and oilseed flax. Flax straw biomass can be baled into three bale types: small rectangular bales, big round bales, and big square bales The main requirements for fuel flax biomass bales are recommended. The boiler for burning flax straw bales must be chosen taking into account the shape and size of the bales. For the efficient operation of boilers, it is necessary to take into account the recommended values of bale bulk density and moisture content of flax biomass.

DOI: 10.36910/acm.vi48.779

To cite this article:
Dudarev, I., & Khomych, A. (2022). Low-quality flax straw biomass harvesting for subsequent use as fuel: a review. *Agricultural Machines*, *48*, 15-29. https://doi.org/10.36910/acm.vi48.779

УДК 631.558:677.11

ТЕХНОЛОГІЯ ЗБИРАННЯ НИЗЬКОЯКІСНОЇ ЛЛЯНОЇ БІОМАСИ ДЛЯ ПОДАЛЬШОГО ЇЇ ВИКОРИСТАННЯ ЯК ПАЛИВА: ОГЛЯД

І.М. Дударєв[1*], **А.В. Хомич**[2]

[1]*Луцький національний технічний університет, Луцьк, Україна*
[2]*Любешівський технічний коледж, Любешів, Україна*

AGRICULTURAL MACHINES
СІЛЬСЬКОГОСПОДАРСЬКІ МАШИНИ

Ключові слова:
збирання льону,
лляна біомаса,
тюки льоносоломи,
спалювання лляної соломи,
тверде паливо

Історія публікації:
Отримано 22.07.2022
Затверджено 25.08.2022

****Автор для листування:***
i_dudarev@ukr.net

АНОТАЦІЯ

Несприятливі умови для вирощування льону, його збирання та вилежування є причиною отримання низькоякісної біомаси льону. Ця біомаса не може бути перероблена на волокно чи інші цілі. Тому низькоякісну льоносолому спалюють на полях або використовують як добриво шляхом заорювання в ґрунт, що зумовлює негативний вплив на навколишнє середовище та ускладнює проведення подальших технологічних операцій з ґрунтом. У статті представлені граничні значення якісних показників стебел льону, льоносоломи та лляної трести, за яких вони придатні для промислового перероблення або отримана лляна біомаса придатна лише для використання у вигляді палива. Низькоякісна лляна біомаса є недорогою, екологічною та відновлюваною сировиною, яку можна використовувати як тверде паливо для опалення теплиць або будівель, що розташовані поблизу поля, де вирощують льон. У статті представлені різні технології збирання льону-довгунця та льону олійного. Також рекомендується технологія збирання низькоякісного льону, що передбачає технологічні операції: брання або скошування льону, обмолочування льону, формування валка льоносоломи, природне сушіння льоносоломи на полі, формування тюків льоносоломи, транспортування тюків льоносоломи, спалювання тюків льоносоломи. Цю технологію збирання можна використовувати для льону-довгунця та льону олійного, що мають низьку якість. Лляну біомасу можна спресовувати у три типи тюків: малі прямокутні тюки, великі круглі тюки (рулони) та великі квадратні тюки. У статті рекомендовані основні вимоги до паливних тюків лляної біомаси. У статті також зазначено, що котел для спалювання льоносоломи необхідно вибирати з урахуванням форми і розміру тюків. Для ефективної роботи котлів необхідно враховувати рекомендовані значення щільності тюків і вологості лляної біомаси.

DOI: 10.36910/acm.vi48.779

Цитувати цю статтю:
Дударєв, І. М., & Хомич, А. В. (2022). Технологія збирання низькоякісної лляної біомаси для подальшого її використання як палива: огляд. *Сільськогосподарські машини*, *48*, 15-29. https://doi.org/10.36910/acm.vi48.779

INTRODUCTION AND PROBLEM STATEMENT

Human energy consumption can be broadly grouped under three headings: heat, grid electricity, and transportation fuels (*Gomez et al., 2008*). Plant biomass, which is inexpensive, ecofriendly and renewable, can be converted to various forms of energy through numerous thermochemical conversion processes, depending upon the type of energy desired (*Tushar et al., 2010*). Using biomass materials in their original form, in particular transport, store, and utilize, is very complicated, because of high moisture content, irregular shape and sizes, and low bulk density (*Kaliyan & Vance Morey, 2009*). Therefore, before removal from the field the biomass densification into bales is conducted.

Using biomass reduces the consumption of fossil fuels and limits the emission of CO_2, SO_x, NO_x and heavy metals (*Naik et al., 2010*). To generate energy, the plant biomass can be burned directly or after its conversion into carbonized solid fuel (biochar), liquid fuel (bioethanol, biodiesel, bio-oil), or gaseous fuel (biogas) (*Ioelovich, 2015*). Pyrolysis is one of the most promising thermo-chemical process, which converts biomass to liquid, gaseous and solid fractions under an oxygen absence condition (*Zhao et al., 2011*).

Plant biomass in the form of wood and fibers are utilized as raw materials for burning for energy and considered as an important renewable source of biofuels (*Demura & Ye, 2010*). For example, co-products, which are obtained during hemp processing, content cellulose and hemicellulose and can be profitably processed for producing 2nd generation bioethanol, which is used to produce energy for the industrial (*Zatta et al., 2010*). Also, for different crops, straw briquetting is an effective way of utilization of straw resources, because after biomass compressing its density is increased to about 1000–1200 kg/m^3, and its volume is reduced by 8–10 times (*Chen et al., 2022*). The following types of fuel briquettes are produced: rectangular bricks with a dimensions of 65×95×150 mm; round cylindrical briquettes with a diameter of 60–90 mm and length of 50–300 mm; polyhedron briquettes (Pini-Kay) with a hole in the center and dimensions 50–80×200–300 mm *(Pavlov, 2020*). Calorific value of biomass from different plant is as following: wheat straw 20.3±0.2 MJ/kg, barley straw 15.7±0.3 MJ/kg, flax straw 17.0±0.2 MJ/kg, timothy grass 16.7±0.3 MJ/kg, pinewood 19.6±0.2 MJ/kg (*Naik et al., 2010*).

Plant biomass contains lignocellulose, which forms the structural framework of plants consisting of cellulose, hemicellulose and lignin, and which is broken down and hydrolyzed into simple fermentable sugars, which upon fermentation form biofuels such as ethanol (*Chaturvedi & Verma, 2013*). The sources of biomass for biofuels need to be produced in a sustainable way and before the potential biomass production in a particular region it is important to identify the degree of climatic adaptation by most suitable plant species for this purpose (*Kerckhoffs & Renquist, 2013*). The yields of crops, which are used as biomass sources, need to be achievable with minimal energy inputs for crop cultivation, planting, nutrient production and application, harvesting and transporting (*Henry, 2010*). Also, it is necessary to consider that food crops rich in starch and sugar, which is basically used for biofuel production, can cause an imbalance in the food and feed supply chain (*Ning et al., 2021*).

Biofuels are classified as primary, which are used in an unprocessed form mainly for heating, cooking (wood chips and pellets, fuelwood), and secondary, which are produced by processing of biomass (ethanol biodiesel etc.) and classified as first, second, and third generation biofuels depending on the kind of raw material used and the technology employed for their production (*Chakraborty et al., 2012*).

There are two types of flax, oilseed flax (linseed) and fibre flax, which are different in their botany, morphogenesis, environment requirements, and techniques of cultivation and harvesting (*Anthony, 2005; Heller et al., 2015*). Fibre flax is mainly cultivated for its fiber (*Omer et al., 2020*). The oilseed flax is predominantly the source of valuable oil, which is contained in seeds and is the source of omega-3 fatty acids (*Zuk et al., 2015*). Also, seeds are a source of protein, soluble polysaccharides, phenolic acids and flavonoids and other biologically active components (*Vinogradov et al., 2012*). Oilseed flax stems make up a considerable part of the oilseed flax biomass, that are considered a by-product of no value (*Sankari, 2000*). But, oilseed flax stems are rich in high potential fibers (*Bar, 2022*), which is shorter in length than long line fiber from fibre flax. In general, oilseed flax straws are buried in the fields or burnt, which are not good solutions for the environment and from an economical point of view (*Khan et al., 2021*). The tough stem fibers in flax straw decay slowly, creating a difficult condition for farming, as a result, farmers traditionally burn flax straw after raking it into piles (*Harry et al., 2014*). Smoke from flax straw fires may obscure public roadways and compromise the health of neighboring residents (*Chen et al., 2005*). Burning flax straw biomass residue also has agronomic disadvantages including loss of 98 to 100% of nitrogen (N), 70 to 90% of sulfur (S), and 20 to 40% of phosphorus (P) and potassium (K) (*Heard et al., 2006*).

The entire flax yield can be used to produce various types of fuel. Flax seeds are a raw material for the production of biodiesel, which can be used as one of the alternative fuel in diesel engines (*Asokan et al., 2021*). Flax biomass, which is cheap and available raw material, can also be used as fuel. Flax straw biomass contains cellulose (27.4 wt%) and hemicellulose (24.8 wt%) and lignin (21.2 wt%) (*Mukhambet et al., 2022*). During the extraction of flax fibers, a by-product, flax shives, is obtained, which is a lignified part of the flax stem and which has a calorific value of 17.25 kJ/g (*Lugovoy et al., 2021*). Flax shives are used for burning in burners or for producing fuel pellets and briquettes (*Rentsen, 2010*), which have a calorific value of 18 MJ/kg (*Komlajeva & Adamovics, 2012*). In addition, liquid bio-fuel can be produced using flax shives (*Mohabeer et al., 2019*), in particular the second generation ethanol can be produced (*González-García et al., 2009*).

In case of unfavorable weather conditions during the cultivation and harvesting of flax, the morphological characteristics and properties of the flax stalks may not be acceptable for the extraction of fiber. Therefore, according an economic point of view, it is better to use low-quality flax straw as fuel after seed separating. In particular, low-quality flax straw can be formed into fuel bales (*Yaheliuk et al., 2020*). For farmers, to collect their own or neighbors' flax straw and burn it in burners of large barn or greenhouse can be profitable. But, if the distance between the field and the place of flax bale using is significant, the transport costs may overtake cost savings of using flax straw (*Flax straw and fibre past and present uses, n.d.*). Also, flax straw biomass utilization is linked to the problems of its harvesting (cutting, baling), transporting and storage (*Mladenović et al., 2009*).

The Goal of the Study is to review the fibre flax and oilseed flax harvesting, as well as the harvesting technique of low-quality flax straw, which can be used as solid fuel.

FLAX

The quality and yield of flax are varied greatly in response to weather conditions, soil type, varieties, cultivation techniques and other factors (*Casa et al., 1999; Pisupati, 2021*). Fibre flax stems have a diameter about 1.4–1.6 mm and a total height of 1.1–1.2 m (*Nag et al., 2015*), and one of the highest slenderness factor (i.e. the ratio between height and diameter of the stem) among botanical herbs and trees, which is about 365±33 (*Goudenhooft et al., 2019*). In the world, the yield of fibre flax straw is varied widely from 220 kg/ha to 4370 kg/ha depending on the country and weather conditions of cultivation (*Zając et al., 2012*). The seed yield is ranged from 270 kg/ha to 890 kg/ha (*Dmitrevskaya et al., 2016*).

Lodging is a major problem for fibre flax as it complicates the harvesting, causes damage to the flax stems and can cause the impossibility of extracting fiber. The risk of flax lodging increases with rainfall, wind, and a high slenderness ratio due to self-weight and additional loads such as rain (*Goudenhooft et al., 2019*). Also, the flax stability to lodging is strongly linked to the seeding rate, flax varieties and nutrients availability, especially to high nitrogen amounts (*Gibaud et al., 2015*). For fibre flax, a seeding rate of 1800 seeds/m^2 is the better compromise long fibre yield, fibre mechanical performances and stem stability to lodging (*Bourmaud et al., 2016*). In the case of significant lodging of flax, further its processing is complicated, therefore it is advisable to use its biomass as fuel.

Oilseed flax plants are typically shorter than the fibre flax plants due to their branched growth (*Kymalainen et al., 2004*). Oilseed grows to a height of 0.40 to 0.91 m (*Anthony, 2005*). To obtain increased seed yield, oilseed flax is sown with a density 25–55 kg/ha, as in this case stem branching is stimulated (*Nag et al., 2015*). The seed yield of oilseed flax is varied widely from 202 kg/ha to 1991 kg/ha depending on the country and weather conditions of cultivation (*Lafond et al., 2008; Zając et al., 2012; Zhang et al., 2020*) and the straw yield is ranged from 2360 kg/ha to 3190 kg/ha (*Rudik, 2016*). The seeds of both the fibre flax and oilseed flax contain 20–40% oil and can be used to obtain oils (*Zhang et al., 2011*).

FIBRE FLAX HARVESTING

Nowadays, the technological level of flax harvesting systems may be considered advanced enough to fully exploit the crop to harvest seeds and retted stems at the same time (*Pari et al., 2015*). The sequence of technological processes during flax harvesting depends on the flax destination and whether it is fibre flax or oilseed flax. Let's consider the sequence of processes for fibre flax harvesting.

The combine harvesting is the most common technology for fibre flax harvesting (**Fig. 1**). This technology makes it possible to obtain flax raw material for the production of long and short fiber, as well as seeds that can be used for processing and sowing. According to the technology, flax combine pulls the fibre flax out and lays it back down on the field into flax band for dew retting. During dew retting, fungi and bacteria partially decompose the flax stems. Flax stems in the flax band are placed parallel. Also, flax seed bolls (seed capsules) are threshed by combine and obtained flax heap is processed outside the field.

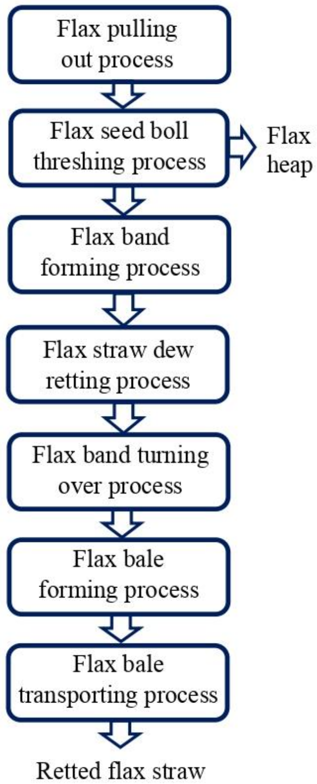

Fig. 1 – Diagram of fibre flax combine harvesting

The duration of dew retting process depends on weather conditions. To reach a good dew retting levels for flax straw, fibre flax production areas must have a mild and humid climate (*Grégoire et al., 2021*), while oilseed flax cultivars are rather grown in continental climate regions (*Zuk et al., 2015*). For uniform dew retting of fibre flax, the thickness of the flax band should be 1–3 stems. If the thickness of the flax band exceeds the recommended value, the lower fibre flax stems may rot. For uniform dew retting process, the flax band turns over 180 degrees once or twice. The first turning over of the flax band is recommended during 8–12 days after flax pulling out. If the heterogeneity of the flax straw quality in the upper and lower layers of the flax band is presented the flax band turn again over 180 degrees after 5–7 days. The flax band are also turned over before forming flax bale. During turning over, the flax straw dries and separates from the soil and grass. Before flax bale forming, the flax band is doubled, that increases the productivity of the round straw baler. Bales remain randomly inside the field or stacking at a specific location close to one of the field's edges (*Vahdanjoo et al., 2021*). Then, flax bales are transported from the field for further retted flax straw processing.

The two-phase flax harvesting is technology for fibre flax harvesting (**Fig. 2**), that is used during adverse weather conditions. According to the technology, the fibre flax is pulled out with flax puller and flax band of unthreshed and paralleled stems is formed. For natural drying and ripening of seeds in bolls, the flax band is laid down on the field. Then, a flax pickup thresher is used, which picks up the flax band, threshes the seed bolls and lays flax band back down on the field for dew retting. A flax heap is threshed outside the field. To improve the dew retting conditions, the flax band is turned over once or twice. Flax bale forming process is the next stage of the two-phase flax harvesting involves. And flax bale transporting for processing is the last stage of two-phase flax harvesting.

If it is necessary to obtain high-quality flax fiber, the fibre flax is pulled out with flax puller. The flax band of unthreshed and paralleled stems is formed on the field for dew retting (**Fig. 3**). During dew retting, the flax band is turned over once or twice. After dew retting, the flax band of unthreshed flax stems is formed into bales and transported for processing. According to the technology, the flax seed bolls are threshed in the conditions of the processing plant during the unwinding of the bales.

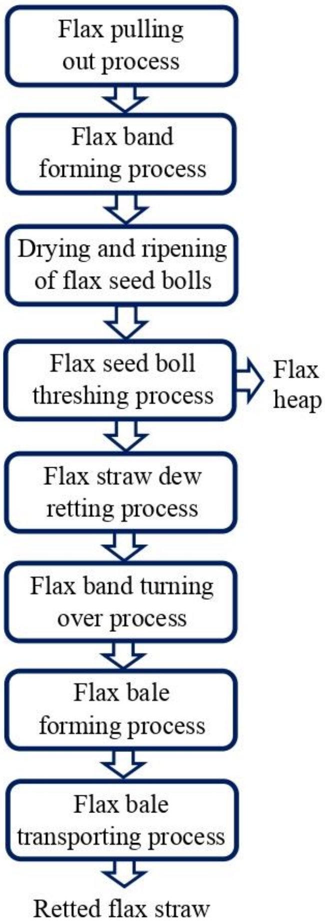

Fig. 2 – Diagram of fibre flax two-phase harvesting

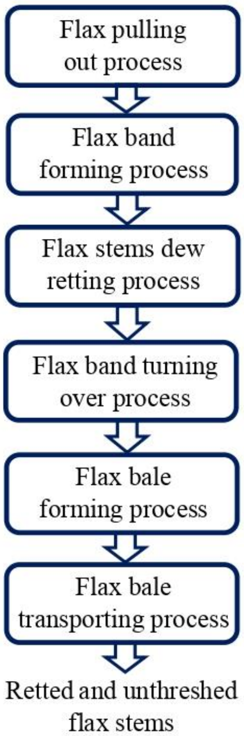

Fig. 3 – Diagram of fibre flax two-phase harvesting to obtain high-quality flax fiber

For fibre flax harvesting, different machines are used such as flax harvester, flax puller, flax band lifting and threshing (rippling) machine, flax band turner, flax band doubling machine, round baler, bale loader and bale truck (*Dudarev, 2020*).

OILSEED FLAX HARVESTING

According to the combine harvesting, oilseed flax is cut with a combine harvester, which is also threshed the flax, cleaned the seeds and formed windrow from crushed flax straw, where straw is dried in a natural way (**Fig. 4**). When using flax straw as fuel, the flax straw windrows are formed into bales with a baler (Variant 1). Then the bales of crushed flax straw are transported to the location where the boiler is placed for straw bale burning. When using flax straw as a fertilizer, crushed straw is plowed into the soil (Variant 2).

In the case of unfavorable weather conditions, the two-phase harvesting of oilseed flax is applied (**Fig. 5**). Oilseed flax is cut and formed into windrows with a mower. After natural drying and ripening of the flax seeds in bolls, the flax windrows are picked up and threshed with a combine harvester. Crushed and dried flax straw is formed into bales (Variant 1) or left on the field as fertilizer (Variant 2).

For oilseed flax harvesting, different machines and equipment are used such as combine harvester, mower, plow, flax round baler, flax bale loader, bale truck, and flax straw bale boiler.

Straw of certain varieties of oilseed flax is used to extract short fiber. In this case, the technologies of fibre flax harvesting are used to harvest oilseed flax (**Fig. 1**, **Fig. 2**).

LOW-QUALITY FLAX STRAW BIOMASS HARVESTING

Under favorable conditions during flax cultivation, flax harvesting and dew-retting, the retted flax straw is obtained, which can be processed for fiber or other purposes (**Fig. 6**). But, in the case of unfavorable conditions at these steps of flax manufacturing process, the low-quality flax straw biomass, the processing of which is unprofitable, can be obtained. It is advisable to use this biomass as a renewable energy source.

During the flax cultivation, unfavorable conditions, including adverse weather conditions, flax diseases and pests, insufficient or excessive use of fertilizers, weediness of flax and flax damage by herbicides, deteriorate the quality of flax straw biomass (**Fig. 6**). As a result, flax can be stunted, weedy, damaged by herbicides, diseases and pests. Also, the length and diameter of flax stalks and the fiber content can be unacceptable for flax straw processing. It is not advisable to leave low-quality flax biomass on the field for dew retting, as it is unsuitable for extracting fiber. After flax threshing and flax straw natural drying, the flax straw biomass can be formed into bales and used as fuel.

During harvesting, flax can also be affected by unfavorable conditions, such as adverse weather conditions, untimely harvesting of flax, wrong choice of flax harvesting technology and incorrect operating regimes of harvesting machines (**Fig. 6**). Unfavorable conditions lead to the deterioration of quality indicators of flax straw. Weather conditions are the most influential, as heavy rain and wind can cause lodging of flax and delay harvesting, which lead to flax yield losses and deterioration of the quality of flax biomass. In the case of incorrect operating regimes of harvesting machines, mechanical damage to the flax stems is possible. Also, it is possible the thickened flax band forming with tangled stalks. As a result, the conditions for flax straw dew retting are worsened. To minimize flax yield losses, the technology of flax harvesting should be chosen taking into account the condition of the grown flax and the weather conditions.

As a result of unfavorable weather conditions during flax straw dew retting, the quality of flax straw can significantly deteriorate. In particular, the tensile strength of the flax fiber and the color of the flax straw can be worse than recommended (**Fig. 6**). Therefore, during flax growing, harvesting and dew retting, it is necessary to analyze the flax biomass and make decisions about its further use and the application of technological processes.

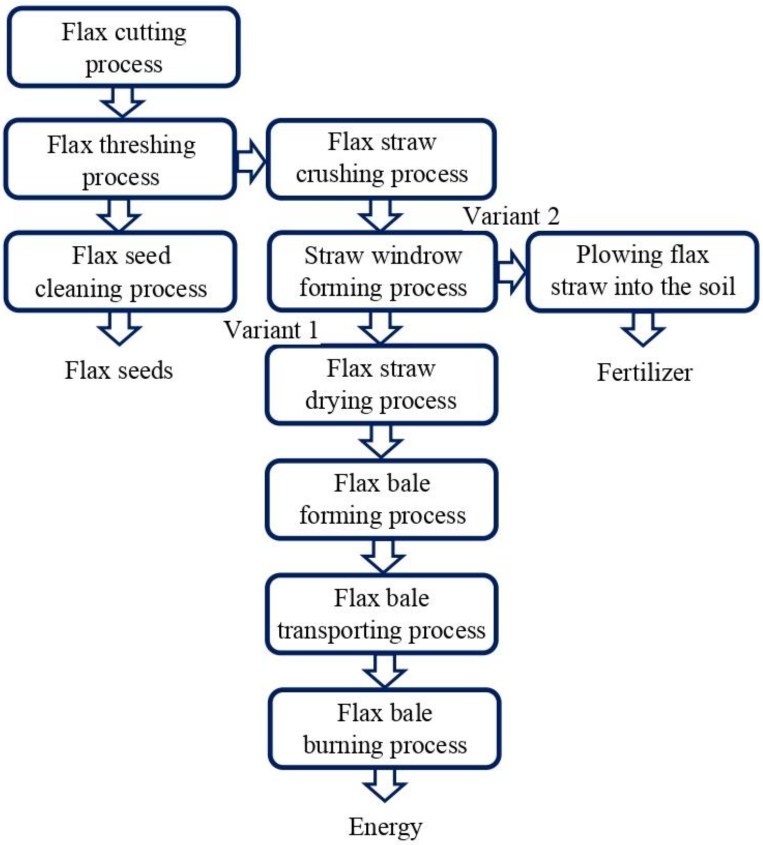

Fig. 4 – Diagram of oilseed flax combine harvesting

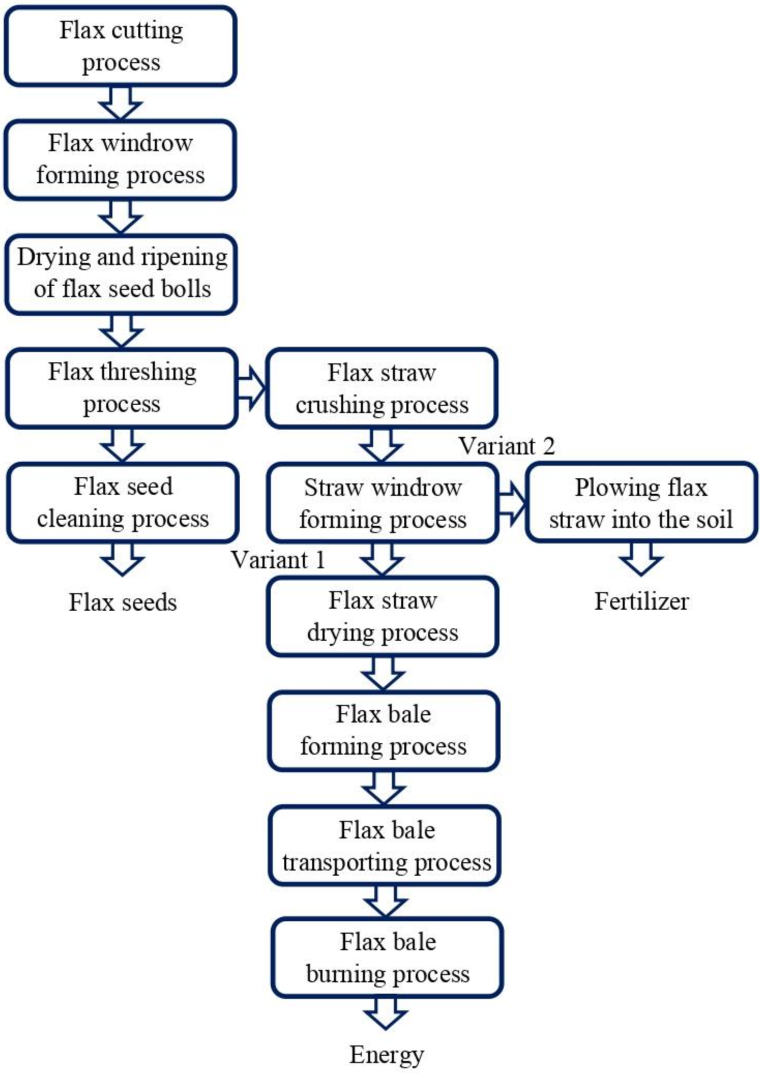

Fig. 5 – Diagram of oilseed flax two-phase harvesting

If the quality properties of flax biomass obtained during flax manufacturing process do not correspond to the allowed (limit) values necessary for its processing (**Table 1**, **Table 2**), then it is advisable to use flax biomass as biofuel. So, the recommended processes of low-quality flax harvesting are as follows: flax pulling out or flax cutting; flax threshing; flax straw windrow forming; flax straw natural drying on the field in natural way; flax bale forming; flax bale transporting; flax bale burning (**Fig. 7**). This harvesting technology can be used for low-quality fibre flax and oilseed flax.

For low-quality flax straw biomass harvesting, different machines and equipment are used such as combine harvester or flax harvester, flax round baler, flax bale loader, flax bale truck and flax bale boiler.

BIOMASS BALES

An important process of harvesting low-quality flax straw biomass is its forming into bales for transporting, storage and burning. Flax straw biomass bales are formed with balers, which pick up flax straw windrow, compress it into bales of even size and weight, and tie them by means of twine. The main requirements for fuel bales are the following: high and uniform bulk density of bale layers; low and uniform moisture content of flax straw in the bale; convenience of transporting and storage; possibility of compact bale packing; low consumption of the twine during bole forming; correspondence of the bale dimensions to the boiler chamber. If bales size is larger than the size of the combustion chamber, it is necessary to disintegrate or cut the bales, which requires additional using of equipment.

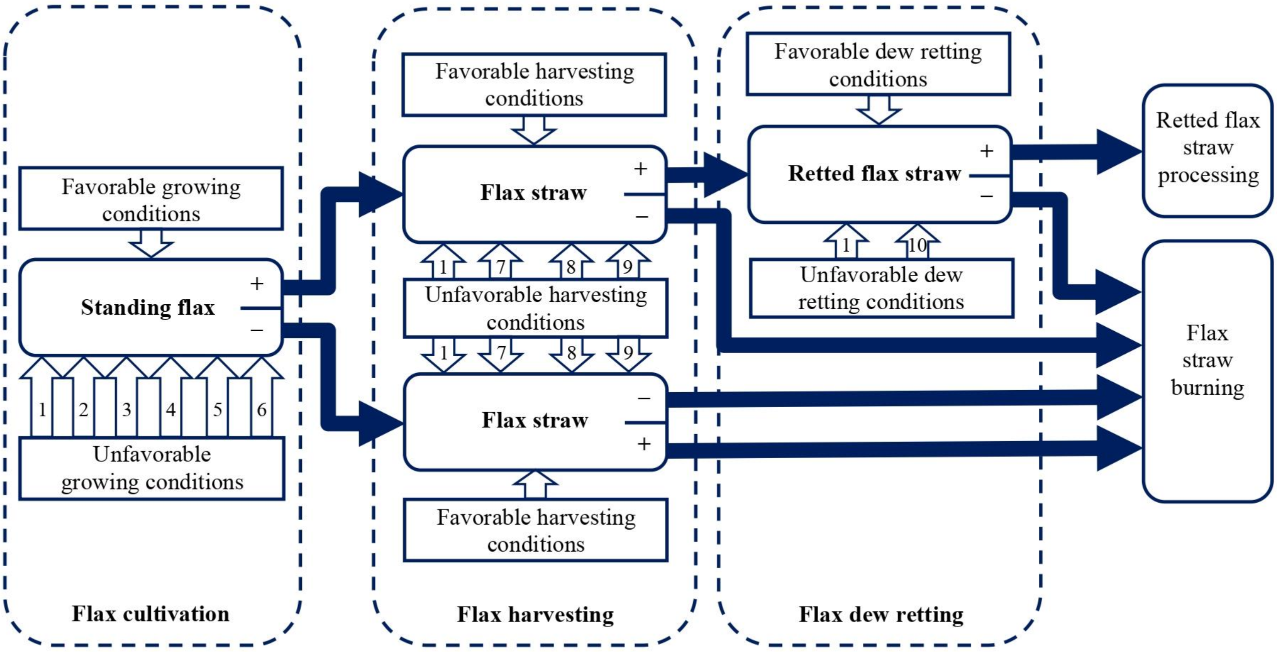

Fig. 6 – Diagram of the influence of growing, harvesting and dew retting conditions on the flax biomass suitability for its processing or burning:
1 – adverse weather conditions; 2 – flax diseases; 3 – flax pests; 4 – insufficient or excessive use of fertilizers; 5 – weediness of flax; 6 – flax damage by herbicides; 7 – untimely harvesting of flax; 8 – wrong choice of flax harvesting technology; 9 – incorrect operating regimes of harvesting machines; 10 – untimely flax band turning over and flax bale forming;
«+» – flax biomass is suitable for processing; «–» – flax biomass is suitable only for burning

Table 1 – The limit values of quality properties of fibre flax stem, flax straw and retted straw for their processing (*GOST 28285-89, 1990; GOST 24383-89, 1990*)

Quality properties	Flax stem	Flax straw	Retted straw
Technical stem (straw) length, m	≥ 0.6	≥ 0.6	≥ 0.6
Fiber (bast) content* or output of long fiber**, %	≥ 20.0*	≥ 20.0*	≥ 5.0**
Fiber tensile strength, daN	≥ 15.0	≥ 15.0	≥ 15.0
Stem (straw) color	yellow, yellow-green, green and yellow-brown	yellow, yellow-green, green and yellow-brown	brown, yellow, gray
Weed content, %	≤ 10.0	≤ 10.0	≤ 10.0
Moisture content, %	-	≤ 23.0	≤ 23.0
Damage by fungal diseases	minor degree	minor degree	minor degree

Table 2 – The limit values of quality properties of oilseed flax, flax straw and retted straw for their processing (*Holovenko, et al., 2019*)

Quality properties	Flax stem	Flax straw	Retted straw
Technical stem (straw) length, m	≥ 0.15	≥ 0.15	≥ 0.15
Fiber (bast) content, %	≥ 11.0	≥ 11.0	≥ 11.0
Stem (straw) color	yellow, yellow-green, green and yellow-brown	yellow, yellow-green, green and yellow-brown	brown, yellow, gray
Weed content (impurity), %	≤ 20.0	≤ 20.0	≤ 20.0
Moisture content, %	≤ 25.0	≤ 25.0	≤ 25.0
Damage by fungal diseases	minor degree	minor degree	minor degree

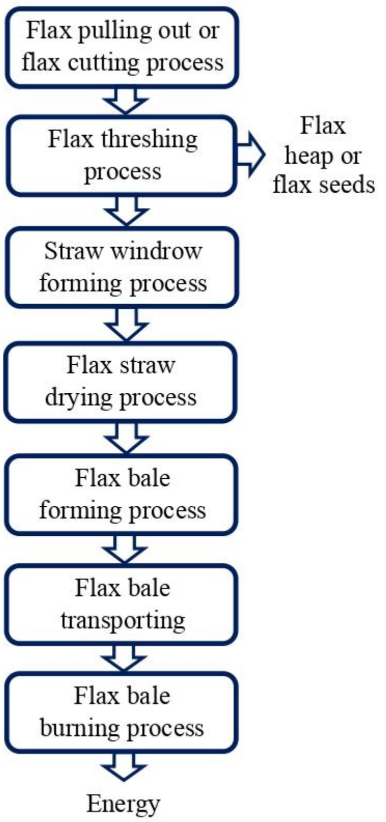

Fig. 7 – Diagram of low-quality flax straw biomass harvesting

The deformation of biomass bales during transporting, storage and manipulation is not allowed. Straw biomass, in particular can be baled into three bale types (**Fig. 8**): small rectangular bales (weighing up to 25 kg); big round bales (in the range of 245 kg to 400 kg); big square bales (in the range of 120 kg to 600 kg) (*Guerrieri et al., 2019*). Small rectangular bales have the following advantages: high packing pressure; low consumption of the twine; ease of transportation; good storage conditions; completely mechanized manipulation (*Mladenović et al., 2009*). Rectangular bales more efficiently fill the available shipping volume on trucks and storages compared to large round bales (*Shinners et al., 1996*). Small rectangular bales have density in the range of 114 kg/m^3 to 207 kg/m^3 (*Hunt, 2001; Afzalinia, 2005*).

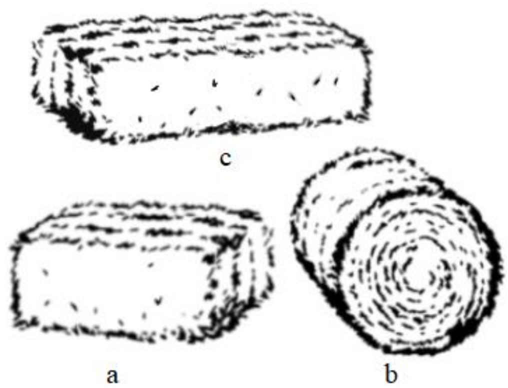

Fig. 8 – Bale types of flax straw biomass:
a – small rectangular bale; b – big round bale;
c – big square bale

Cylindrical (round) bale is the most common form of bale for flax straw biomass collecting, which is formed with a roll baler. There are two types of roll balers: fixed chamber baler, which has a series of fixed rollers around the bale chamber, and variable (expanding) chamber baler, which has two arms. The bale, which is formed with the fixed chamber, contain a softer/looser core, and the bale, which is formed with the variable chamber, contain harder/tighter core (*Sun et al., 2010*). The shape of round bales provides the ease of their manipulation and transporting, and the low requirements for their storage (*Román & Hensel, 2014*). Round bales have density in the range of 100 kg/m^3 to 170 kg/m^3 (*Hunt, 2001; Afzalinia, 2005*). The main disadvantage of round bales is the uneven distribution of straw along the radius of the bale, which is a negative factor during its burning.

Big square bales have bale cross section of 80×80 cm and maximum bale length about 2.5 m (*Shinners et al., 2000*). Also, big square bales have density in the range of 126 kg/m^3 to 251 kg/m^3 (*Shinners et al., 2000; Descôteaux & Savoie, 2003*).

BIOMASS BALE BURNING

Straw-fired boiler technology has been proven as an attractive method of disposing of agricultural residues (*Dedovic et al., 2012*). The process of straw bale burning, which is placed in a thermal chamber of boiler, has following pattern: straw bale loading, straw bale drying and heating, straw bale burning with the release of volatile substances, afterburning of residues, removal of slags (*Pochanin, 2007*). There are two main types of bale boilers: batch-fired straw boilers in which the entire bale is loaded into the furnace and cigar-type boilers in which the bales continuously enter the burning chamber. The combustion chamber of bale boilers may either be cylindrical or cubic in shape (*Kristensen & Kristensen, 2004*). Each time the furnace door of batch-fired straw boiler is opened and a new bale is fed into the furnace the temperature and CO emission peaks are occurred. This makes cigar firing organization much more suitable, since it preserves the continuity of the combustion process, in contrast there are no sudden changes of temperature and harmful products emissions in cigar-type boilers (*Mladenović et al., 2009*). Also, combustion biomasses can cause different problems such as: slagging; premature corrosion of the furnace metallic components; the high level of alkalis in crop residues may lead to aerosol formation, resulting in ash melting temperature drop, fouling and emission issues (*Morissette et al., 2013*).

During straw burning, the furnace temperature can reach about 700°C and more (*Lu et al., 2009*). Straw moisture content must be limited to below 25% to prevent excessive CO emission without compromising the burning equipment (*Yang et al., 2007*). The proximate composition of flax straw is presented in **Table 3** (*Okolie et al., 2020; Tushar et al., 2012*). According to the straw moisture content of 16% and the bale bulk density of 135 kg/m^3, the straw consumption in boiler is reached about 26.3 t/h and boiler efficiency is reached about 92% (*Yang et al., 2007*).

Table 3 – Proximate analysis of flax straw (*Okolie et al., 2020; Tushar et al., 2012*)

Component	Value
Moisture, wt%	8.4–9.3
Ash, wt%	2.6–2.9
Volatile matter, wt%	78.8–83.3
Fixed carbon, wt%	4.8–18.3
Carbon, wt%	47.78–49.10
Hydrogen, wt%	5.37–6.10
Nitrogen, wt%	0.84–1.30
Sulfur, wt%	0.12–0.21
Oxygen, wt%	40.50–43.22
Sodium, mg/kg	133
Potassium, mg/kg	5147
Chlorine, mg/kg	588
Higher heating value HHV, MJ/kg	20.04

CONCLUSIONS

Under unfavorable conditions for flax growing, harvesting and dew-retting, the low-quality flax biomass can be obtained. It is impractical to process low-quality flax biomass for fiber, so farmers continue to face the problem of its utilization. As a rule, farmers burn it on the field or use it as fertilizer by plowing into the soil. Burning biomass in the field causes significant damage to the environment. Flax biomass, containing fiber, slowly decomposes in the soil, therefore it complicates the cultivation operations. After threshing the seeds, low-quality flax biomass should be dried in natural way on the field and formed into bales, which can be used as solid fuel for heating greenhouses or buildings located near the field where the flax is grown. The boiler for burning flax straw bales must be chosen taking into account the shape and size of the bales. For the efficient operation of boilers, it is necessary to take into account the recommended values of bale bulk density and moisture content of flax biomass.

REFERENCES

Afzalinia, S. (2005). *Modeling and validation of the baling process in the compression chamber of a large square baler* [Thesis of the Degree of Doctor of philosophy]. University of Saskatchewan, Saskatoon, Canada.

Anthony, W. S. (2005). Development of machines to separate fiber and shive from seed flax straw. *Applied Engineering in Agriculture*, *21*(6), 1057-1063. https://doi.org/10.13031/2013.20022

Asokan, M. A., Prabu, S. S., Prathiba, S., Akhil, V. S., Abishai, L. D., & Surejlal, M. E. (2021). Emission and performance behaviour of flax seed oil biodiesel/diesel blends in DI diesel engine. *Materials Today: Proceedings*, *46*, 8148-8152. https://doi.org/10.1016/j.matpr.2021.03.108

Bar, M., Grégoire, M., Khan, S. U., De Luycker, E., & Ouagne, P. (2022). Studies on classically harvested linseed flax fibers for bio-composite reinforcement and textile applications. *Journal of Natural Fibers*. (in press). https://doi.org/10.1080/15440478.2021.2024934

Bourmaud, A., Gibaud, M., & Baley, C. (2016). Impact of the seeding rate on flax stem stability and the mechanical properties of elementary fibres. *Industrial Crops and Products*, *80*, 17-25. https://doi.org/10.1016/j.indcrop.2015.10.053

Casa, R., Russell, G., Lo Cascio, B., & Rossini, F. (1999). Environmental effects on linseed (Linum usitatissimum L.) yield and growth of flax at different stand densities. *European Journal of Agronomy*, *11*(3-4), 267-278. https://doi.org/10.1016/s1161-0301(99)00037-4

Chakraborty, S., Aggarwal, V., Mukherjee, D., & Andras, K. (2012). Biomass to biofuel: a review on production technology. *Asia-Pacific Journal of Chemical Engineering*, *7*, S254-S262. https://doi.org/10.1002/apj.1642

Chaturvedi, V., & Verma, P. (2013). An overview of key pretreatment processes employed for bioconversion of lignocellulosic biomass into biofuels and value added products. *3 Biotech*, *3*, 415-431. https://doi.org/10.1007/s13205-013-0167-8

Chen, S., Zhao, Y., Tang, Z., Ding, H., Su, Z., & Ding, Z. (2022). Structural model of straw briquetting machine with vertical ring die and optimization of briquetting performance. *Agriculture*, *12*, 736. https://doi.org/10.3390/ agriculture12050736

Chen, Y., Tessier, S., Cavers, C., Xu, X., & Monero, F. (2005). A survey of crop residue burning practices in Manitoba. *Applied Engineering in Agriculture*, *21*(3), 317-323. https://doi.org/10.13031/2013.18446

Dedovic, N., Igic, S., Janic, T., Matic-Kekic, S., Ponjican, O., Tomic, M., & Savin, L. (2012). Efficiency of small scale manually fed boilers – mathematical models. *Energies*, *5*(5), 1470-1489. https://doi.org/10.3390/en5051470

Demura, T., & Ye, Z.-H. (2010). Regulation of plant biomass production. *Current Opinion in Plant Biology*, *13*(3), 298-303. http://doi.org/10.1016/j.pbi.2010.03.002

Descôteaux, S., & Savoie, P. (2003). Development and evaluation of a dryer for big square hay bales. In *CSAE/SCGR 2003 Meeting* (pp. 03-212). Montréal, Québec, Canada.

Dmitrevskaya, I. I., Stepanova, D. S., Belopukhov, S. L., & Mazirov, M. A. (2016). Yield of fiber flax in long-term field experiment. *Zemledelie*, *7*, 42-44. (in Russian)

Dudarev, I. (2020). A review of fibre flax harvesting: conditions, technologies, processes and machines. *Journal of Natural Fibers* (in press). http://doi.org/10.1080/15440478.2020.1863296

Flax straw and fibre past and present uses. Chapter 12. (n.d.). In J. C. P. Dribnenki (ed.), 5th ed., *Growing Flax. Production, Management & Diagnostic Guide*. *Flax Counsil of Canada* (pp. 54-61), Winnipeg Manitoba, Canada.

Gibaud, M., Bourmaud, A., & Baley, C. (2015). Understanding the lodging stability of green flax stems; The importance of morphology and fibre stiffness. *Biosystems Engineering*, *137*, 9-21. http://doi.org/10.1016/j.biosystemseng.2015.06.005

Gomez, L. D., Steele-King, C. G., & McQueen-Mason, S. J. (2008). Sustainable liquid biofuels from biomass: the writing's on the walls. *New Phytologist*, *178*, 473-485. https://doi.org/10.1111/j.1469-8137.2008.02422.x

González-García, S., Luo, L., Moreira, M. T., Feijoo, G., & Huppes, G. (2009). Life cycle assessment of flax shives derived second generation ethanol fueled automobiles in Spain. *Renewable and Sustainable Energy Reviews*, *13*(8), 1922-1933. http://doi.org/10.1016/j.rser.2009.02.003

GOST 24383-89. (1990). Retted stalks. Requirements for State Purchases *(ГОСТ 28285-89. (1990). Треста льняная. Требования при заготовках. Издательство стандартов)*. (in Russian)

GOST 28285-89. (1990). Flax straw. Requirements for State Purchases *(ГОСТ 28285-89. (1990). Солома* *льняная. Требования при заготовках. Издательство стандартов)*. (in Russian)

Goudenhooft, C., Alméras, T., Bourmaud, A., & Baley, C. (2019). The remarkable slenderness of flax plant and pertinent factors affecting its mechanical stability. *Biosystems Engineering*, *178*, 1-8. https://doi.org/10.1016/j.biosystemseng.2018

Grégoire, M., Bar, M., De Luycker, E., Musio, S., Amaducci, S., Gabrion, X., Placet, V., & Ouagne, P. (2021). Comparing flax and hemp fibres yield and mechanical properties after scutching/hackling processing. *Industrial Crops and Products*, *172*, 114045. https://doi.org/10.1016/j.indcrop.2021.114045

Guerrieri, A. S., Anifantis, A. S., Santoro, F., & Pascuzzi, S. (2019). Study of a large square baler with innovative technological systems that optimize the baling effectiveness. *Agriculture*, *9*(5), 86. https://doi.org/10.3390/agriculture9050086

Harry, I., Ibrahim, H., Thring, R., & Idem, R. (2014). Catalytic subcritical water liquefaction of flax straw for high yield of furfural. *Biomass and Bioenergy*, *71*, 381-393. https://doi.org/10.1016/j.biombioe.2014.09.017

Heard, J., Cavers, C., & Adrian, G. (2006). Up in smoke – nutrient loss with straw burning. *Better Crops*, *90*, 10-11.

Heller, K., Sheng, Q. C., Guan, F., Alexopoulou, E., Hua, L. S., Wu, G. W., Jankauskiene, Z., & Fu, W. Y. (2015). A comparative study between Europe and China in crop management of two types of flax: linseed and fibre flax. *Industrial Crops and Products*, *68*, 24-31. https://doi.org/10.1016/j.indcrop.2014.07.010

Henry, R. J. (2010). Evaluation of plant biomass resources available for replacement of fossil oil. *Plant Biotechnology Journal*, *8*(3), 288-293. https://doi.org/10.1111/j.1467-7652.2009.00482.x

Holovenko, T., Kozel, V., Shovkomud, O., Puts, V., & Nazarchuk, L. (2019). Innovative methodology and software for quality control of new bast raw material with oilseed flax. *Fibres and Textiles*, *2*, 18-24.

Hunt, D. (2001). *Farm power and machinery management* (10th ed.). Ames, Iowa, the USA. Iowa State University Press.

Ioelovich, M. (2015). Recent findings and the energetic potential of plant biomass as a renewable source of biofuels – a review. *BioResources*, *10*(1), 1879-1914.

Kaliyan, N., & Vance Morey, R. (2009). Factors affecting strength and durability of densified biomass products. *Biomass and Bioenergy*, *33*(3), 337-359. https://doi.org/10.1016/j.biombioe.2008.08.005

Kerckhoffs, H., & Renquist, R. (2013). Biofuel from plant biomass. *Agronomy for Sustainable Development*, *33*, 1-19. https://doi.org/10.1007/s13593-012-0114-9

Khan, S. U., Labonne, L., Ouagne, P., & Evon, P. (2021). Continuous mechanical extraction of fibres from linseed flax straw for subsequent geotextile applications. *Coatings*, *11*(7), 852. https://doi.org/10.3390/coatings11070852

Komlajeva, L., & Adamovics, A. (2012). Evaluation of flax (Linum usitatissimum L.) quality parameters for bioenergy production. *Engineering for Rural Development*, *11*, 490-495.

Kristensen, E. F., & Kristensen, J. K. (2004). Development and test of small-scale batch-fired straw boilers in Denmark. *Biomass and Bioenergy*, *26*(6), 561-569. https://doi.org/10.1016/j.biombioe.2003.09.006

Kymalainen, H., Koivula, M., Kuisma, R., Sjoberg, A.-M., & Pehkonen, A. (2004). Technologically indicative properties of straw fractions of flax, linseed (Linum usitatissimum L.) and fibre hemp (Cannabis sativa L.). *Bioresource Technology*, *94*(1), 57-63. https://doi.org/10.1016/j.biortech.2003.11.027

Lafond, G. P., Irvine, B., Johnston, A. M., May, W. E., McAndrew, D. W., Shirtliffe, S. J., & Stevenson, F. C. (2008). Impact of agronomic factors on seed yield formation and quality in flax. *Canadian Journal of Plant Science*, *88*, 485-500.

Lu, H., Zhu, L., & Zhu, N. (2009). Polycyclic aromatic hydrocarbon emission from straw burning and the influence of combustion parameters. *Atmospheric Environment*, *43*(4), 978–983. https://doi.org/10.1016/j.atmosenv.2008.10.022

Lugovoy, Y., Chalov, K., Kosivtsov, Y., Sidorov, A., & Sulman, M. G. (2021). Slow pyrolysis of flax production waste. *Chemical Engineering Transactions*, *88*, 331-336. https://doi.org/10.3303/CET2188055

Mladenović, R., Dakić, D., Erić, A., Mladenović, M., Paprika, M., & Repić, B. (2009). The boiler concept for combustion of large soya straw bales. *Energy*, *34*(5), 715-723. https://doi.org/10.1016/j.energy.2009.02.003

Mohabeer, C., Reyes, L., Abdelouahed, L., Marcotte, S., Buvat, J.-C., Tidahy, L., Abi-Aad, E., & Taouk, B. (2019). Production of liquid bio-fuel from catalytic de-oxygenation: Pyrolysis of beech wood and flax shives. *Journal of Fuel Chemistry and Technology*, *47*(2), 153-166. https://doi.org/10.1016/s1872-5813(19)30008-8

Morissette, R., Savoie, P., & Villeneuve, J. (2013). Corn stover and wheat straw combustion in a 176-kw boiler adapted for round bales. *Energies*, *6*(11), 5760-5774. https://doi.org/10.3390/en6115760

Mukhambet, Y., Shah, D., Tatkeyeva, G., & Sarbassov, Y. (2022). Slow pyrolysis of flax straw biomass produced in Kazakhstan: Characterization of enhanced tar and high-quality biochar. *Fuel*, *324*(B), 124676. https://doi.org/10.1016/j.fuel.2022.

124676

Nag, S., Mitra, J., & Karmakar, P. G. (2015). An overview on flax (Linum usitatissimum L.) and its genetic diversity. *International Journal of Agriculture, Environment and Biotechnology*, *8*(4), 805-817. https://doi.org/10.5958/2230-732X.2015.00089.3

Naik, S., Goud, V. V., Rout, P. K., Jacobson, K., & Dalai, A. K. (2010). Characterization of Canadian biomass for alternative renewable biofuel. *Renewable Energy*, *35*(8), 1624-1631. https://doi.org/10.1016/j.renene.2009.08.033

Ning, P., Yang, G., Hu, L., Sun, J., Shi, L., Zhou, Y., Wang, Z., & Yang, J. (2021). Recent advances in the valorization of plant biomass. *Biotechnology for Biofuels*, *14*, 102. https://doi.org/10.1186/s13068-021-01949-3

Okolie, J. A., Nanda, S., Dalai, A. K., & Kozinski, J. A. (2020). Hydrothermal gasification of soybean straw and flax straw for hydrogen-rich syngas production: Experimental and thermodynamic modeling. *Energy Conversion and Management*, *208*, 112545. https://doi.org/10.1016/j.enconman.2020.112545

Omer, T. A., Amal, M. A. El-Borhamy, & Maysa, S. Abd. El-Sadek. (2020). Effect of harvesting dates and seeding rates on yield and yield components of some flax varieties. *Journal of Plant Production*, *11*(12), 1501-1505. https://doi.org/10.21608/jpp.2021.55272.1012

Pari, L., Baraniecki, P., Kaniewski, R., & Scarfone, A. (2015). Harvesting strategies of bast fiber crops in Europe and in China. *Industrial Crops and Products*, *68*, 90-96. https://doi.org/10.1016/j.indcrop.2014.09.010

Pavlov, S. B. (2020). Improving the efficiency of the flax complex in Novgorod region. *IOP Conf. Series: Earth and Environmental Science*, *613*, 012104. https://doi.org/10.1088/1755-1315/613/1/012104

Pisupati, A., Willaert, L., Goethals, F., Uyttendaele, W., & Park, C. H. (2021). Variety and growing condition effect on the yield and tensile strength of flax fibers. *Industrial Crops and Products*, *170*, 113736. https://doi.org/10.1016/j.indcrop.2021.113736

Pochanin, Y. (2007). Selection of optimal patterns of straw burning in heating plants *(Выбор рациональных схем сжигания соломы в тепловых установках)*. In *Sakharov Readings 2007: Environmental Problems of the XXI Century* (pp. 274-275). (in Russian)

Rentsen, B. (2010). *Characterization of flax shives and factors affecting the quality of fuel pellets from flax shives* [Thesis of the Degree of Master of Science]. University of Saskatchewan, Saskatoon, Canada.

Román, F. D., & Hensel, O. (2014). Numerical simulations and experimental measurements on the distribution of air and drying of round hay bales. *Biosystems Engineering*, *122*, 1-15. https://doi.org/10.1016/j.biosystemseng.2014.03.008

Rudik, Al. L. (2016). Agrotechnology aspects to the assessment of oil flax growing of double use. *Ekologiya & Stroitelstvo*, *3*, 15-22. (in Russian)

Sankari, H. S. (2000). Linseed (Linum usitatissimum L.) cultivars and breeding lines as stem biomass producers. *Journal of Agronomy and Crop Science*, *184*(4), 225-231. https://doi.org/10.1046/j.1439-037x.2000.00375.x

Shinners, K. J., Barnett, N. G., & Schlesser, W. M. (2000). Measuring mass-flow-rate and moisture on a large square baler. In *2000 ASAE Annual International Meeting* (pp. 001037). Milwaukee, WI.

Shinners, K. J., Straub, R. J., Huhnke, R. L., & Undersander, D. J. (1996). Harvest and storage losses associated with mid-size rectangular bales. *Applied Engineering in Agriculture*, *12*(2), 167-173. https://doi.org/10.13031/2013.25636

Sun, Y., Buescher, W., Lin, J., Schulze Lammers, P., Ross, F., Maack, C., Cheng, Q., & Sun, W. (2010). An improved penetrometer technique for determining bale density. *Biosystems Engineering*, *105*(2), 273-277. https://doi.org/10.1016/j.biosystemseng.2009. 09.020

Tushar, M. S. H. K., Mahinpey, N., Khan, A., Ibrahim, H., Kumar, P., & Idem, R. (2012). Production, characterization and reactivity studies of chars produced by the isothermal pyrolysis of flax straw. *Biomass and Bioenergy*, *37*, 97-105. https://doi.org/10.1016/j.biombioe.2011.12.027

Tushar, M. S. H. K., Mahinpey, N., Murugan, P., & Mani, T. (2010). Analysis of gaseous and liquid products from pressurized pyrolysis of flax straw in a fixed bed reactor. *Industrial & Engineering Chemistry Research*, *49*(10), 4627-4632. https://doi.org/10.1021/ie902036v

Vahdanjoo, M., Nørremark, M., & Sørensen, C. G. (2021). A system for optimizing the process of straw bale retrieval. *Sustainability*, *13*(14), 7722. https://doi.org/10.3390/su13147722

Vinogradov, D. V., Polyakov, A. V., & Kuntsevich, A. A. (2012). Influence of technology of growing on yield and oil chemical composition of linseed in Non-chernozem zone of Russia. *Journal of Agricultural Sciences*, *57*(3), 135-142. https://doi.org/10.2298/JAS1203135V

Yaheliuk, S., Didukh, V., Busnyuk, V., Boyko, G., & Shubalyi, O. (2020). Optimization on efficient combustion process of small-sized fuel rolls made of oleaginous flax residues. *INMATEH – Agricultural Engineering*, *62*(3), 361-368. https://doi.org/10.35633/inmateh-62-38

Yang, Y. B., Newman, R., Sharifi, V., Swithenbank, J., & Ariss, J. (2007). Mathematical modelling of straw combustion in a 38MWe power plant furnace and effect of operating conditions. *Fuel*, *86(*1-2), 129-142. https://doi.org/10.1016/j.fuel.2006.06.023

Zając, T., Oleksy, A., Klimek-Kopyra, A., & Kulig, B. (2012). Biological determinants of plant and crop productivity of flax (Linum usitatissimum L.). *Acta Agrobotanica*, *65*(4), 3-14. https://doi.org/10.5586/aa.2012.016

Zatta, A., Vecchi, S., Gobbo, R., & Monti, A. (2010). Complementary use of long and short hemp fibres and shives for textile and second generation biofuels. In *18th European Biomass Conference and Exhibition* (pp. 427-428), 3–7 May 2010, Lyon, France.

Zhang, Q., Gao, Y., Yan, B., Cui, Z., Wu, B., Yang, K., & Ma, J. (2020). Perspective on oil flax yield and dry biomass with reduced nitrogen supply. *Oil Crop Science*, *5*(2), 42-46. https://doi.org/10.1016/j.ocsci.2020.04.004

Zhang, Z.-S., Wang, L.-J., Li, D., Li, S.-J., & Özkan, N. (2011). Characteristics of flaxseed oil from two different flax plants. *International Journal of Food Properties*, *14*(6), 1286-1296. https://doi.org/10.1080/10942911003650296

Zhao, X., Zhang, J., Song, Z., Liu, H., Li, L., & Ma, C. (2011). Microwave pyrolysis of straw bale and energy balance analysis. *Journal of Analytical and Applied Pyrolysis*, *92*(1), 43-49. https://doi.org/10.1016/j.jaap.2011.04.004

Zuk, M., Richter, D., Matuła, J., & Szopa, J. (2015). Linseed, the multipurpose plant. *Industrial Crops and Products*, *75*, Part B, 165-177. https://doi.org/10.1016/j.indcrop.2015.05.005