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Production and Properties of Apple Pomace Pellets and their Suitability for Energy Generation Purposes

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1. Introduction

The food processing industry, including fruit and vegetable processing sectors, produce significant quantities of environmental pollutants, including liquid pollutants such as wastewater, as well as biodegradable waste (Rejak & Mościcki 2006). Food processing is a complex process because raw materials, which are supplied on a seasonal basis, spoil easily and may be a source of microbiological contamination during production (Ajila et al. 2012, Kumider 2006, Nadulski & Grochowicz 2001, Royer 2006) Food processing waste poses a significant problem for both, the producers and the environment (Bernstad & Jansen 2012, Borycka 2009, Darlington et al. 2009, Fronc & Zawirska 1994, Gassara et al. 2011, Grochowicz 1993, Gullón et al. 2007, Heras-Ramírez et al. 2009, Jakubowski 2009). In 2005-2011, annual apple production in Poland ranged from 1,877,000 to 2,626,000 tons (Statistical Yearbook of Agriculture 2011).

Pomace is the main waste component during the production of apple juice. Owing to its unique sensory attributes, apple pomace is used in the production of feed and pectin. Pomace is a good binder, and it is also processed by extrusion. The properties of pomace, its management options and the suitability for the production of environmentally-friendly composite materials are investigated by research centers around the world (Dhillon et al. 2011, Dhillon et al. 2012, Duda-Chodak et al. 2011, Joshi & Sandhu 1996, Kavargiris et al. 2009, Kumar et al. 2010, Kumider & Zielnica 2006, Limousy et al. 2012, Mahawar et al. 2012, Nawirska & Kwaśniewska 2004, Rhee & Park 2010, Shalini & Gupta 2010, Suárez et al. 2010, Sudha et al. 2007, Wang et al. 2007). The use of apple pomace in animal feed production was discussed by Grochowicz & Kusińska (1983), Soska (1988) and Joshi & Sandhu (1996). Apple pomace can be managed by pressing and this method is referred to as pressure agglomeration. This technique has been thoroughly investigated by Skonecki (2004) and Heim (2005). Pressed pomace is used in industrial processing and power generation. This is one of the easiest pomace management methods, in particular in regions where large amounts of waste cannot be quickly processed or where transport is not an option due to considerable distance. No detailed studies addressing the above applications were found in literature. General information about pressure agglomeration of plant materials as well as analyses of compressed materials can be found in the papers by Grochowicz et al. (2004), Hejft (2002), Kulig & Laskowski (2006) and Zawiślak (2006).

2. Aim of the study

The aim of this study was to determine the energy consumption of the pressure agglomeration process of dry apple pomace, and selected physicochemical properties of compressed material. These findings were used to evaluate the suitability of processed apple pomace for energy generation purposes. The analyzed material was ground to increase the accuracy of analytical results.

The study involved:

- determination of the size distribution of apple pomace fractions,
- pressure agglomeration, determination of compaction energy and expansion of samples directly after pressing and after 24 hours.

The heat of combustion of the analyzed apple pomace was determined and compared with other fruit and vegetable processing waste.

The results of this study expand the knowledge base accumulated in the work of Shah & Masoodi (1994) and Shalini & Gupta (2010).

3. Materials and methods

The experimental material was supplied by a fruit and vegetable processing plant in the Mazowsze Voivodship (Poland). Apple pomace was produced in between 20 and 30 September 2010, at the peak of the season of apple juice and concentrate production. The pomace had a moisture content of 82%. The material was then dried in a laboratory drier at 100°C in order to obtain a final moisture content of 8 %. Ground and unground pomace was analyzed at three stages. Stage I involved a size distribution analysis. Every test was carried out with the use of ten sieves with the following mesh opening sizes:

- for unground apple pomace: 2.00, 1.50, 1.20, 1.00, 0.75, 0.60, 0.49, 0.43, 0.30, 0.02 mm,
- for ground apple pomace: 2.00, 1.50, 1.00, 0.75, 0.49, 0.30, 0.25, 0.10, 0.06, 0.02 mm.

Representative samples of 100 g (±0.05 g) each were weighed and poured into the top sieve of a shaking screen. The samples were sieved for three minutes at 300 rpm. Relative air humidity was 35% and temperature was 20°C. The resulting pomace fractions were weighed. The results are presented in Figures 2 and 3.

At stage II, the samples were subjected to pressure agglomeration in the INSTRON 8802 universal testing machine. Every sample had the weight of Z=0.150 g (±5 mg). The material was poured into an 8 mm cylinder of the pressing unit (Fig. 1). The samples were subjected to compaction load of: 199 MPa, 398 MPa, 597 MPa, 796 MPa and 995 MPa. The desired pressure was produced by modifying the load applied to the piston of the hydraulic press in the INSTRON 8802 machine. The load applied to the press piston was 10 kN, 20 kN, 30 kN, 40 kN and 50 kN, respectively.

The compaction energy of samples was determined with the use of a BLUEHILL-2 application for controlling the INSTRON 8802 machine. The theoretical aspects of energy consumption in the pressing process were discussed by Czaban & Kamiński (2003). The samples were removed from the press, and their height (thickness) was measured without determinations of their moisture content. The same parameter was measured again after 24 hours, and percentage changes between both measurements were calculated. To guarantee repeatable results, measurements were performed by one person with the use of identical equipment, and samples were stored in an exsiccator at 20°C.

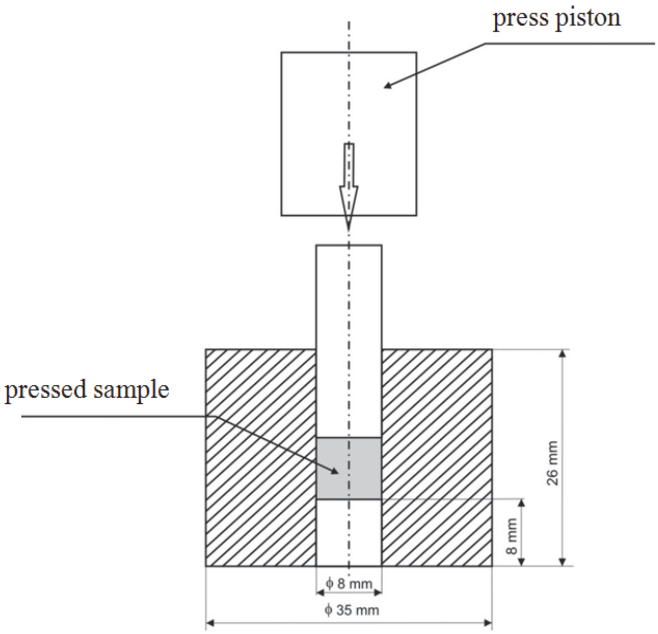

Fig. 1. Diagram of the pressing unit
Rys. 1. Schemat komory zagęszczania

The compaction energy of samples was determined with the use of a BLUEHILL-2 application for controlling the INSTRON 8802 machine. The theoretical aspects of energy consumption in the pressing process were discussed by Czaban & Kamiński (2003). The samples were removed from the press, and their height (thickness) was measured without determinations of their moisture content. The same parameter was measured again after 24 hours, and percentage changes between both measurements were calculated. To guarantee repeatable results, measurements were performed by one person with the use of identical equipment, and samples were stored in an exsiccator at 20°C.

Due to insignificant differences in measurement results, every test was performed in three to five replications.

Energy consumption of the compaction process was determined with the use of a coefficient of compaction energy per unit of material (W). The above coefficient was calculated using formula (1):

$$W = \frac{A}{Z} \tag{1}$$

At stage III of the experiment, the heat of combustion was determined. Measurements were performed on pomace samples stored in the exsiccator, 24 to 36 hours after drying.

The heat of combustion of the tested samples was measured in a KL-12 calorimeter manufactured by Precyzja-Bit. The sample was placed in a pressure vessel and burned in an oxygen atmosphere.

The samples weighed approximately 600 mg (±1 mg). The applied load was 53 kN, i.e. the pressure inside the press with a diameter of 11 mm was equal to 557.7 MPa. The samples were placed in a crucible and secured with a piece of thread used for suspending the sample on a resistance wire, which constitutes a part of the ignition system. The crucible was then placed inside the calorimeter which was supplied with oxygen to drive out atmospheric air. The calorimeter was placed in a vessel filled with water, electrodes were attached and the calorimeter was closed. Water was stirred with an electric agitator. Preliminary, main and final combustion was controlled by a computer using an algorithm developed by Precyzja-Bit. Successive phases of combustion, including sample ignition, were displayed on the screen, analyzed and calculated, and the final heat of combustion was determined in $J \cdot g^{-1}$.

At the final stage (IV), compacted samples were viewed under a stereoscopic microscope to determine differences between samples of ground and unground material.

4. Results and discussion

4.1. Sieve analysis

The aim of the analysis was to determine the size of pomace fractions deposited on sieves with different mesh sizes.

The first sieve analysis of unground samples revealed a predominance of large pomace particles. 96.8% of the particles were deposited on a sieve with 2.00 mm mesh openings, and the smallest number of particles was found on a sieve with 0.43 mm and 0.22 mm mesh openings. The size of pomace particles resulted from the apple grinding technology in the processing plant. The results are presented in Figure 2.

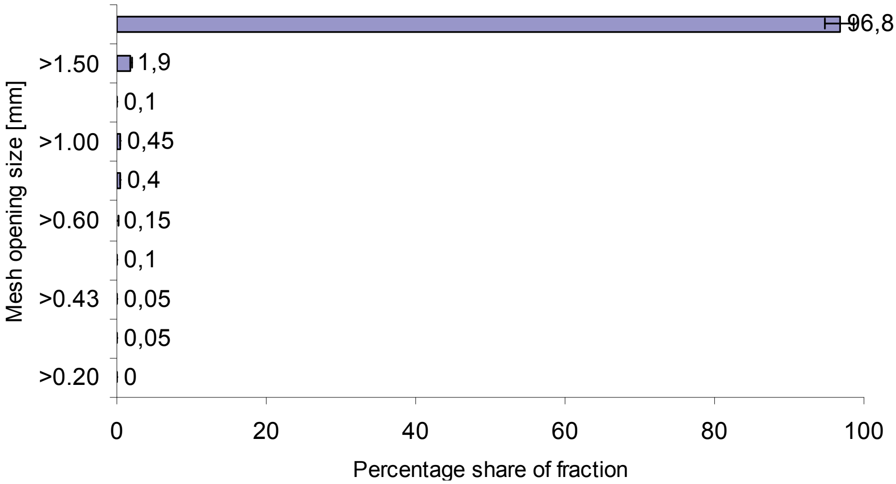

Fig. 2. Percentage share of unground pomace fractions subjected to a sieve analysis
Rys. 2. Udział procentowy cząstek niezmielonych wytłoków poddanych analizie sitowej

The following sieve analysis was performed on ground samples. Particles larger than 1.5 mm were the predominant fraction, but the share of particles smaller than 1.5 mm increased significantly to more than 43%. The results are presented in Figure 3.

The following conclusions can be drawn from the results of the sieve analysis:

- grinding leads to changes in the size of particles deposited on a given sieve,
- grinding removes large particles which could produce negative consequences at latter stages of processing,

- grinding parameters should be selected in view of the intended use of ground material in order to prevent any negative effects in further stages of processing.

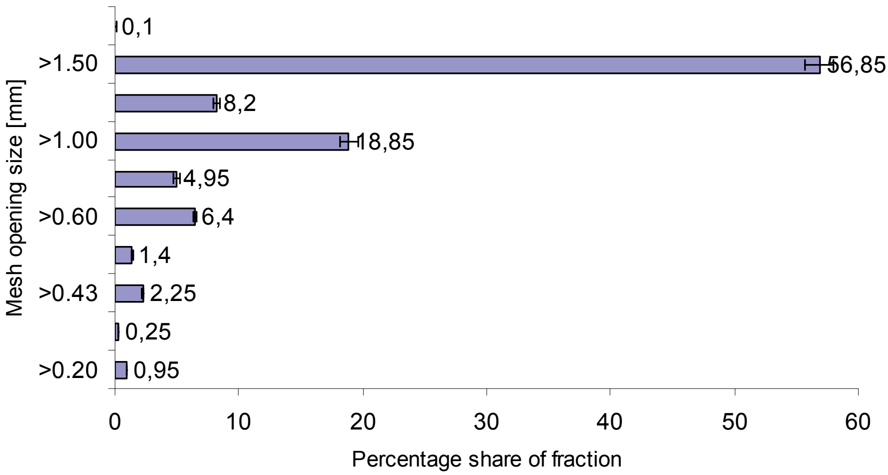

Fig. 3. Percentage share of ground pomace fractions subjected to a sieve analysis
Rys. 3. Udział procentowy cząstek zmielonych wytłoków poddanych analizie sitowej

4.2. Compaction

Trace amounts of apple seed oil were observed on the internal surface of the press cylinder during compaction (Fig. 1). The compaction energy of pomace, determined by the load applied to dry ground and unground apple pomace samples, is presented in Figure 4.

An analysis of the above results indicates that:

- energy consumption was insignificantly higher for unground samples,
- the greatest difference in compaction energy was observed for smaller loads of 10 kN and 20 kN,
- ground samples were more easily compacted.

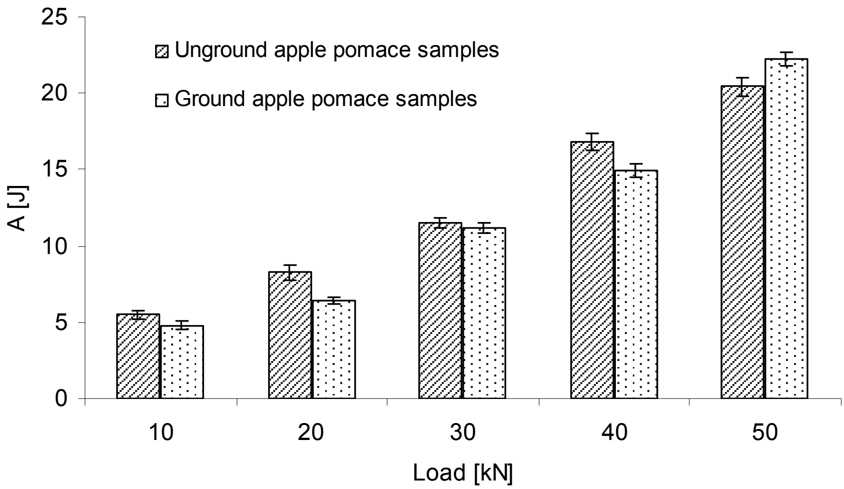

Fig. 4. Compaction energy A [J] at different values of the load applied to ground and unground samples
Rys. 4. Energia zagęszczania A [J] przy różnych wartościach zadanego obciążenia dla zmielonych i niezmielonych wytłoków

Images of compacted samples were enlarged under a microscope and presented in Figure 5 and 6.

Large fragments (particles) of compacted apple pomace are visible in Figure 5. The exact contours of pressed fragments (particles) can be observed. Some fragments began to protrude from the compacted surface, as shown in the bottom left corner of the image.

An image of a compacted sample of ground apple pomace is presented in Figure 6. Particle contours are less visible, and there are no noticeable signs of pomace fragments protruding from the compacted surface.

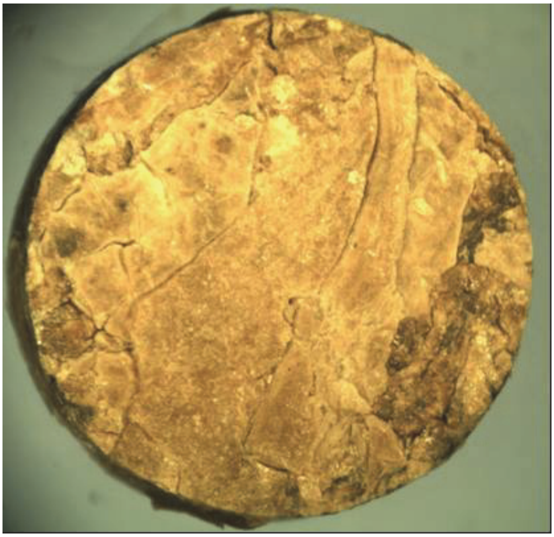

Fig. 5. Image of a unground sample of apple pomace compacted under 50 kN load (20x magnification)
Rys. 5. Obraz niezmielonych wytłoków jabłkowych sprasowanych pod obciążeniem 50 kN (20x powiększenie)

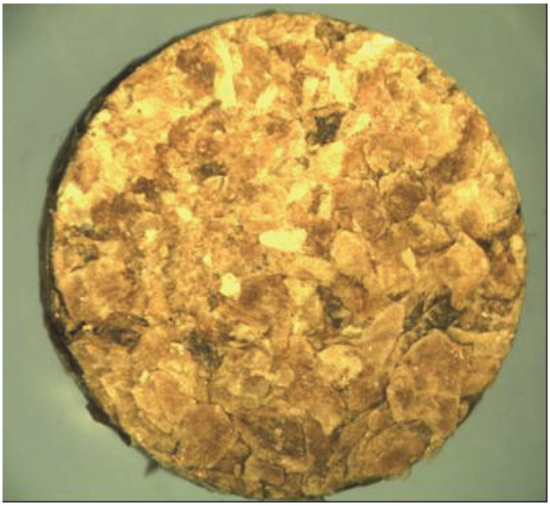

Fig. 6. Image of a ground sample of apple pomace compacted under 50 kN load (20x magnification)
Rys. 6. Obraz zmielonych wytłoków jabłkowych sprasowanych pod obciążeniem 50 kN (20x powiększenie)

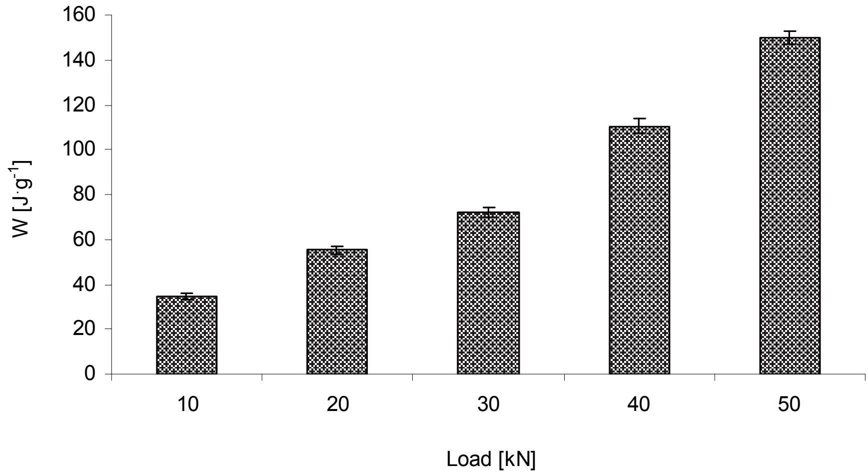

Fig. 7. Compaction energy of ground pomace per unit *W* [J·g^{-1}] for different loads
Rys. 7. Energia zagęszczania zmielonych wytłoków W [J·g^{-1}] dla różnych obciążeń

The results of the analysis indicate that total compaction energy per unit of unground pomace ranged from 66.60 to 150.00 J·g^{-1}. The respective energy range of ground samples was 34.79 to 149.95 J·g^{-1} (Fig. 7), at a temperature of 20°C and relative air humidity of 31.7%. Temperature and relative humidity represent average values from the range measured during the experiment.

A significant correlation between load (F) and compaction energy per unit (W) is described by regression equation (2):

$$W = 2.855 \cdot F - 1.208 \text{ at } R^2 = 0.965 \qquad (2)$$

According to Skonecki (2004) total specific compaction energy for other plant materials (pea, barley, maize, lupine, wheat bran, wheat, rapeseed meal, soybean meal) varied from 9.65 to 12.97 J·g^{-1} in the load range of 14.20 to 42.72 MPa. Differences in compaction energy resulted mainly from the chemical composition and moisture content of the analyzed material. The density values of samples subjected to different loads are presented in Tables 1 and 2.

Table 1. Density of pellets made from unground apple pomace
at different load values
Tabela 1. Gęstość pelletów z niezmielonych wytłoków jabłkowych
przy różnych wartościach obciążenia

Load [kN]	10	20	30	40	50
Density [$g \cdot dm^{-3}$]	1118.2	1114.0	1129.2	1166.3	1139.1
Regression equation	$\rho = 0.941 \cdot F + 1105.1$ at $R^2 = 0.509$				

Table 2. Density of pellets made from ground apple pomace
at different load values
Tabela 2. Gęstość pelletów ze zmielonych wytłoków jabłkowych
przy różnych wartościach obciążenia

Load [kN]	10	20	30	40	50
Density [$g \cdot dm^{-3}$]	1118.2	1114.0	1128.8	1168.1	1139.1
Regression equation	$\rho = 0.959 \cdot F + 1104.9$ at $R^2 = 0.493$				

At the next stage, the expansion of compacted samples was determined. Expansion was measured directly after removal from the pelleting unit and after 24 hours. The following changes in pomace expansion were observed (Fig. 8 and 9):

- the samples expanded and their height changed after 24 h,
- the greatest difference in height was observed in samples subjected to 10 kN and 20 kN loads,
- the samples were neither deformed nor disintegrated,
- no significant differences were observed between pellets produced from ground and unground material.

The most significant changes in height (thickness) were observed in samples subjected to the smallest loads. Percentage changes in the height of the analyzed samples are shown in Figures 10 and 11.

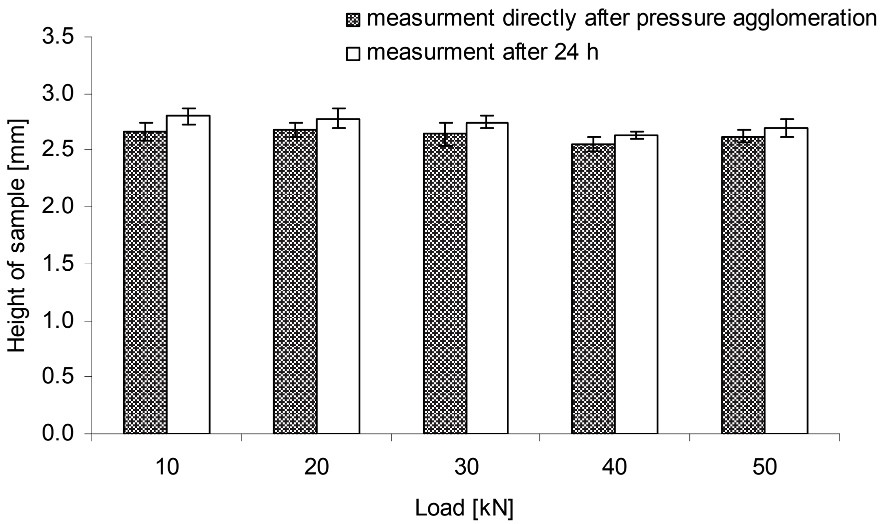

Fig. 8. Expansion of pellets made from unground apple pomace after 24 h
Rys. 8. Rozprężenie pelletów z niezmielonych wytłoków po 24 h

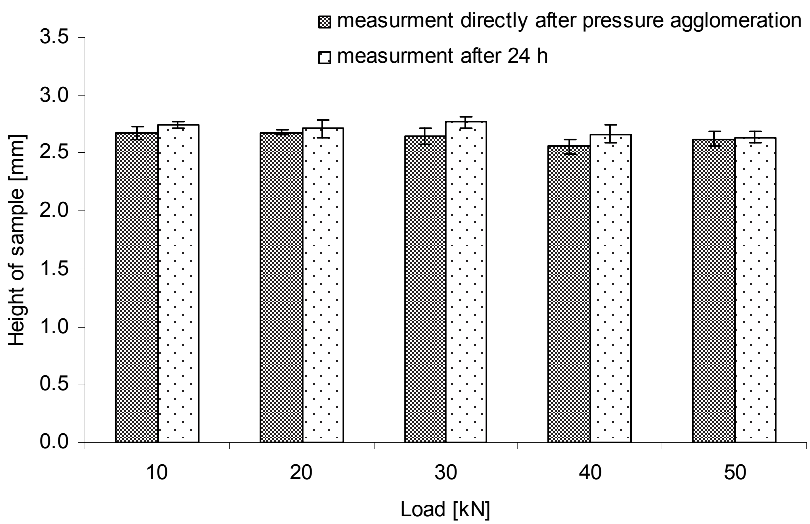

Fig. 9. Expansion of pellets made from ground apple pomace after 24 h
Rys. 9. Rozprężenie pelletów z zmielonych wytłoków po 24 h

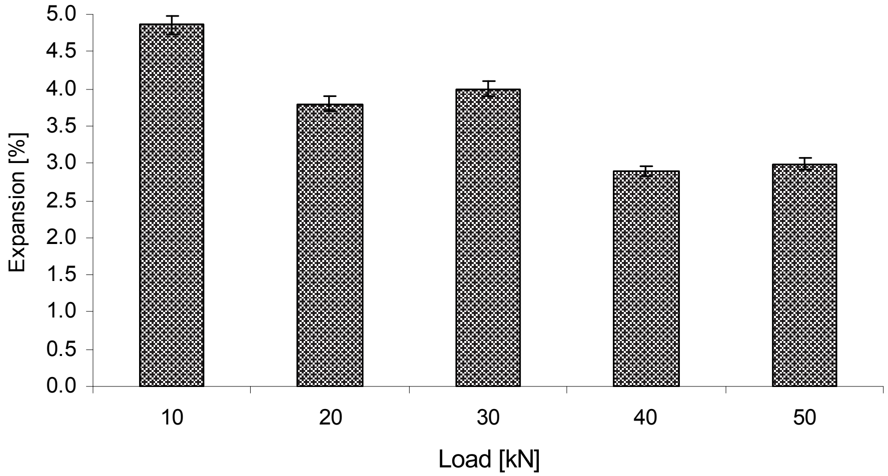

Fig. 10. Increase in the expansion of unground pomace samples after 24 hours
Rys. 10. Wzrost rozprężenia próbek niezmielonych wytłoków po 24 h

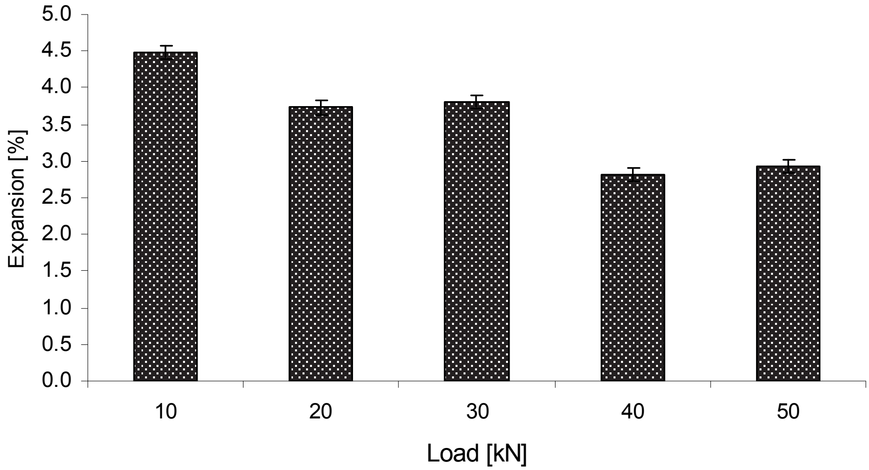

Fig. 11. Increase in the expansion of ground pomace samples after 24 hours
Rys. 11. Wzrost rozprężenia próbek zmielonych wytłoków po 24 h

The above results indicate that:

- expansion did not exceed 5% for both sample types,
- the greatest changes in expansion were reported in samples subjected to 10 kN load,
- the smallest percentage change in sample height (2.7%) was reported for 40 kN load.

It should also be noted than an increase in expansion was accompanied by a decrease in pellet density. Further analyses, such as a dimensional analysis, should be performed to compare the results of our laboratory experiment with the results that are achievable in an industrial environment. The resulting data would constitute sufficient material for a separate paper.

4.4. Heat of combustion

The results of an analysis of the heat of combustion of apple pomace samples are presented in Figure 12.

The heat of combustion of apple pomace was determined at 19 $MJ \cdot kg^{-1}$, and it was lower in comparison with other types of fruit pomace. Ground and unground samples released the same amount of heat. Other pomace types are characterized by higher heat of combustion than the analyzed apple pomace samples, but they have a smaller share of the Polish by-product market and are thus less important for energy generation purposes. Apple pomace is the predominant type of fruit processing waste in Poland. According to Verma et al. (2011), apple pomace is characterized by gross calorific value of 20.31 $MJ \cdot kg^{-1}$ and net calorific value of 17.48 $MJ \cdot kg^{-1}$. The use of pomace in the energy sector could lower fuel costs in fruit and vegetable processing plants (Borycka 2009, Wojdalski 1998). This pomace management method should serve as an example of a "waste-free technology" in fruit and vegetable processing which could directly improve a production plant's energy balance.

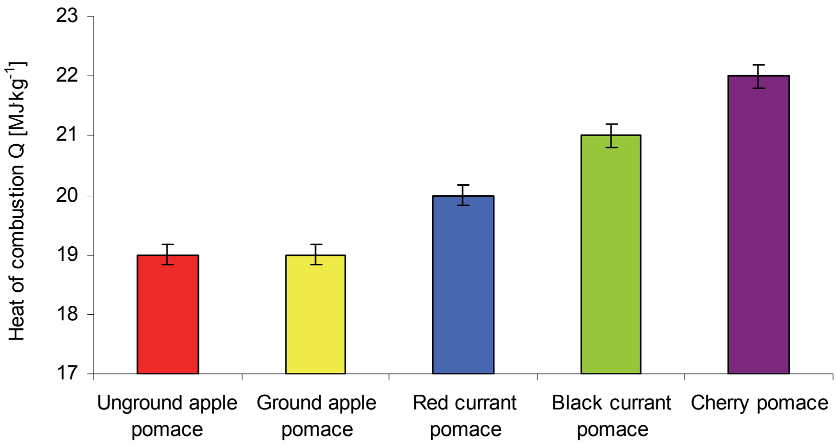

Fig. 12. Heat of combustion of apple pomace and other fruit pomace (average values)
Rys. 12. Ciepło spalania wytłoków jabłkowych i innych wytłoków owocowych (wartości średnie)

Our study adds new findings to previous research conducted by many authors (Chau et al. 2009, Ciunel & Klugmann-Radziemska 2014, Hang 1987, Kowalczyk & Piwnicki 2007, Lisowski et al. 2011, Mirabella et al. 2014, Miranda et al. 2012, Niedziółka at al. 2008, Obidziński 2012, Piecuch 2000, Ravichandran & Corscadden 2014, Reddy et al. 2013, Sargent et al. 1986, Sypuła et al. 2010, Zafari & Kianmehr 2014) who examined various scenarios for using plant biomass in energy generation with an indication of its heat of combustion and calorific value.

If apple pomace has net calorific value of 17.3 MJ·kg^{-1} and the effectiveness of the heating device (steam or water boiler) reaches 70%, the amount of energy generated by the combustion of apple pellets is approximately 80 times higher than the amount of energy consumed during processing under 50 kN load and approximately 340 times higher than the amount of energy consumed during processing under 10 kN load.

5. Conclusions

Apple pomace is a by-product of fruit and vegetable processing, and it constitutes biodegradable waste. Small quantities of pomace are not harmful to the environment, but large amounts of waste could pose a problem for processing plants.

The following conclusions can be drawn from the results of our study:

- the aim of pressure agglomeration was to determine compaction energy of ground and unground pomace at various load values – 10, 20, 30, 40 and 50 kN,
- in the applied range of loads, total compaction energy of unground pomace was determined in the range of 66.60 $J \cdot g^{-1}$ to 150.00 $J \cdot g^{-1}$, and of ground pomace – in the range of 34.79 to 149.95 $J \cdot g^{-1}$ at a temperature of 20°C and relative air humidity of 31.7%,
- with an increase in load, the expansion of unground pomace decreased from 4.86% to 2.99% and of ground pomace – from 4.49% to 2.93%, which points to higher density of pellets made from ground pomace,
- grinding increased the share of pomace particles smaller than 1.5 mm to more than 43% (1.3% before grinding),
- the heat of combustion determined in the calorimeter was 19 $MJ \cdot kg^{-1}$, and it was comparable with that of other types of fruit pomace. The quantity of heat which can be obtained from apple pomace as a source of renewable energy was determined,
- if apple pomace has net calorific value of 17.3 $MJ \cdot kg^{-1}$ and the effectiveness of the heating device reaches 70%, the amount energy generated by the combustion of apple pellets is 80 to 340 times higher than the amount of energy consumed during processing under the load of 50 kN and 10 kN, respectively,
- the management of apple pomace in the production plant could serve as an example of a "waste-free" technology,
- during microscopic observations of compacted samples, the contours of pressed fragments in unground material were clearly visible, whereas the contours of ground material particles could not be clearly identified.

Symbols

A – compaction energy [J]
F – load [kN]
W – compaction energy per unit [$J \cdot g^{-1}$]
Z – sample weight [g]
ρ – density [$g \cdot dm^{-3}$]
Q – heat of combustion [$MJ \cdot kg^{-1}$]

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Wytwarzanie, właściwości i możliwości zagospodarowania na cele energetyczne odpadowych wytłoków z przetwórstwa jabłek

Streszczenie

Przemysł spożywczy, a w tym branża owocowo-warzywna, dostarczają znacznych ilości odpadów i zanieczyszczeń środowiska. Utrudnione jest także prowadzenie produkcji, gdyż surowce do przerobu są dostarczane sezonowo, łatwo ulegają zepsuciu i mogą być źródłem zakażenia mikrobiologicznego. Wytłoki jabłkowe są jednym z odpadów przemysłu owocowo-warzywnego i należą do odpadów biodegradowalnych. Małe ich ilości nie są szkodliwe dla środowiska, lecz duża koncentracja może stanowić problem dla zakładu produkcyjnego. Prasowane wytłoki mogą mieć zastosowanie do wytwarzania produktów użytkowych lub w energetyce. Jest to jedna z metod zagospodarowania wytłoków jabłkowych, szczególnie w rejonach, w których występuje ich nadmiar i nie ma możliwości szybkiego przerobu w celach paszowych lub transport na duże odległości nie jest opłacalny. Przedstawiono problematykę, metodykę badań oraz analizę wyników badań dotyczących właściwości i zagospodarowa-

nia wytłoków jabłkowych. Część badawczą poprzedzono przeglądem literatury, w której zawarto dostępne osiągnięcia w tej dziedzinie. Badaniom poddano wytłoki przed i po rozdrobnieniu. Zakres pracy obejmował:
- analizę składu granulometrycznego w celu określenia wielkości poszczególnych frakcji zawartych w próbkach wytłoków,
- aglomerację ciśnieniową i określenie energii zagęszczania oraz rozprężenie otrzymanych próbek bezpośrednio po prasowaniu i po upływie 24 godzin,
- ustalenie ciepła spalania badanych wytłoków jabłkowych i porównanie z ciepłem spalania innych odpadów z przemysłu owocowo-warzywnego.

Energię zagęszczania badanych próbek ustalano na podstawie odczytów uzyskanych w wyniku stosowania oprogramowania BLUEHILL-2 stosowanego do obsługi maszyny INSTRON 8802. Poddano analizie wytrzymałościowej próbki wytłoków i określano ich rozprężenie po upływie 24-godzinnego przechowywania. Całkowita energia zagęszczania dla pelletów z wytłoków nierozdrobnionych zawierała się w granicach od 66,60 do 150,00 J/g, zaś dla pelletów z wytłoków rozdrobnionych wskaźniki te wynosiły od 34,79 J/g do 149,95 J/g w temperaturze 20°C i wilgotności względnej powietrza 31,7%. Gęstość otrzymanych pelletów wynosiła odpowiednio w granicach 1114,0-1166,3 i 1114,0-1168,1 g/dm^3. Sprasowane próbki badawcze poddano badaniom ciepła spalania w bombie kalorymetrycznej. Ciepło spalania wytłoków jabłkowych wynosiło 19 MJ/kg. Z punktu widzenia opłacalności procesu można stwierdzić, że np. przyjmując wartość opałową wynoszącą 17.3 MJ/kg i sprawność przemian energii w kotle parowym wynoszącą 70%, energia uzyskana ze spalania pelletów jabłkowych może być od 80 do 340 razy większa w porównaniu z zapotrzebowaniem energii na ich produkcję stosując naciski odpowiednio 50 kN i 10 kN. Zagospodarowanie wytłoków jabłkowych bezpośrednio w zakładzie produkcyjnym może być przykładem zastosowania „technologii bezodpadowej". Ponadto zagospodarowanie wytłoków na cele energetyczne może częściowo wpłynąć na wzrost efektywności energetycznej produkcji zakładu owocowo-warzywnego.

Abstract

The food processing industry, including fruit and vegetable processing sectors, produce significant quantities of waste and environmental pollutants. Food processing is a complex and demanding process because raw materials are supplied on a seasonal basis, they spoil easily and may be a source of microbiological contamination during production. Apple pomace is a by-product of fruit and vegetable processing, and it constitutes biodegradable waste. Small quantities of pomace are not harmful to the environment, but large amounts of waste could pose a problem for processing plants. Pressed pomace can be used in industrial processing and power generation. This is one of the easiest pomace management methods, in particular in regions where large amounts of waste cannot be quickly processed into animal feed or where transport is not an option due to considerable distance. This paper presents the methodology and the results of analyses investigating the properties of apple pomace and its management scenarios. A review of published sources discussing the achievements in pomace management precedes the experimental part of this study. Samples of ground and unground apple pomace were analyzed to determine: granulometric composition – the size distribution of apple pomace fractions, pressure agglomeration, compaction energy and expansion of samples immediately after pressing and after 24 hours, the heat of combustion of the analyzed apple pomace, which was compared with the heat of combustion of other fruit and vegetable processing waste.

The compaction energy of samples was determined with the use of a BLUEHILL-2 application for controlling the INSTRON 8802 machine. Material was subjected to compressive strength tests, and the expansion of samples was determined after 24 hours of storage. The total compaction energy of unground pomace ranged from 66.60 to 150.00 $J \cdot g^{-1}$, and of ground pomace from 34.79 to 149.95 $J \cdot g^{-1}$ at a temperature of 20°C and relative air humidity of 31.7%. The density of the resulting apple pomace pellets was determined in the range of 1114.0-1166.3 and 1114.0-1168.1 $g \cdot dm^{-3}$. The heat of combustion of pressed pomace samples, measured in a calorimeter, was 19 $MJ \cdot kg^{-1}$. The results of the study indicate that if apple pomace has net calorific value of 17.3 $MJ \cdot kg^{-1}$ and the effectiveness of a steam boiler reaches 70%, the amount of energy generated by the combustion of apple pellets is 80 to 340 times higher than the amount of energy consumed during processing under the load of 50 kN and 10 kN, respectively. The management of apple pomace in the production plant can serve as an example of a "waste-free" technology. The use of processed apple pomace for energy generation purposes may contribute to improving energy efficiency in production processes in fruit and vegetable processing plants.

Słowa kluczowe:
pellety, aglomeracja ciśnieniowa, wytłoki jabłkowe, energia biomasy, ciepło spalania

Keywords:
pellets, pressure agglomeration, apple pomace, biomass energy, heat of combustion