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Properties of RDF after Prolonged Storage

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Abstract: Increasing production of municipal solid waste (MSW) drives the need for its disposal in a manner that is safe for the environment and human health. However, this may require short- or long-term storage before it can be properly processed. Similarly, a way of processing waste material is necessary for the re-cultivation of dump sites. This article presents the results of an investigation into the effects of long-term open-air storage upon waste material to be turned into refuse-derived fuel (RDF) by standard methods for the assessment of MSW and RDF pellet quality including bomb calorimetry, sieve analysis, furnace drying/burning for water/ash content assessment, and pellet expansion measurements. Results of the investigation indicate that such a form of storage bears no notable negative effect on the quality of the material; the pellet expansion coefficient, heat of combustion, and ash content were all found to be approximate to pre-storage values, with positive implications for the storage of solid waste and the prospects of its subsequent processing into solid fuel. It is shown that such material can be stored in open-air conditions for prolonged periods without the loss of desired parameters. In addition, a discussion of differences between the properties of material drawn from varying depths of the pile is provided and the potential impact of the findings in the context of the production and the storage of refuse-derived fuel is assessed.

Keywords: refuse-derived fuel; solid fuel; sustainable fuel; storage; RDF; waste management; heat of combustion; expansion coefficient

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1. Introduction

It is estimated that the amount of waste generated globally exceeds two billion tons per year and is projected to further increase in the future to an estimated value of ca. 3.5 billion tons by 2050 [1–4]. Such a state of affairs results in a pressing issue of how to dispose of it, and in particular, how to do it in a sustainable manner. Although recognized as a global problem [3,4], it is also dependent on local characteristics; research and policy initiatives aiming to reduce the amount of waste are undertaken in many particular places around the world, e.g., in India [5,6], the United States [7], and the European Union [8,9]. Unless noted, the following article is written primarily in the context of the European Union.

In general, there are several approaches to waste management, listed by various sources, such as:

- Landfilling, composting, incineration, and recycling [7];
- (a) Prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g., energy recovery; and (e) disposal [8,9];
- Recycling, composting, landfilling, incineration, bio-remediation, [and] waste-to-energy [10];
- Reduction in solid waste production; the reuse of recycled materials by different mechanical recycling methods; thermochemical processing such as pyrolysis and gasification; incinerating solid waste and heat recovery networks; sending waste to landfills [11].

Of these, landfilling or disposal (which may include non-recovery incineration) is listed as the least desirable, followed by incineration and/or energy recovery (i.e., repurposing as an energy source as a principal result), followed by recycling and re-use (which may mean the re-use of waste as raw material for industry or the repurposing of used and discarded products for further use). Waste prevention, which apart from the reduction in the quantity of waste produced in the first place (including means such as extension of the life-cycle of a product) may also include a reduction in the impact of the produced goods on the environment and health, is sometimes not listed as a "waste management" method for reasons of addressing the issue before any actual waste is produced; if listed along with the others, it is seen as the most desirable method of waste management [7–11].

A short list of general advantages and disadvantages of these methods of waste management is given in Table 1.

Table 1. Advantages and disadvantages of various approaches to waste management [7–9].

Method	Advantages	Disadvantages
Landfilling	Cheap	Area demand; aesthetically displeasing; methane production; potential soil and water contamination; may attract pests and wild animals
Incineration	Potential for energy production; low space demand	High initial investment; does not promote waste prevention (steady stream of waste required for energy production); ash must be disposed of; possible air pollution
Composting	Potential cheap on-site waste management; non-hazardous and marketable by-products	Time needed to process waste; possible odors; may attract wild animals; only suitable for biological waste
Recycling	Sustainable; potentially cost-saving (reuse of material)	Requires specific policies; may require sorting or processing of waste; potentially not cost-effective without incentives
Prevention	Sustainable; concerned with causes rather than effects; lowers the need for all other methods	Requires industry and society engagement; may require significant overhaul of existing infrastructure; may require changes in/replacement of established industrial processes

Alongside recycling, one of the approaches to this issue that is currently propagated in the EU is to re-purpose the waste into an energy source [12]. This serves the dual role of reducing the amount of waste in landfills and lowering the use of fossil fuels. According to a hierarchy of waste disposal methods established by Directive 2008/98/EC of the European Parliament [8], as noted above, energy recovery is placed below recycling but is preferable to landfilling. Industrial or municipal solid waste (MSW) unsuitable for recycling can therefore be directly incinerated or processed into fuel with precisely defined parameters. Fuel derived in this manner is known as refuse-derived fuel (RDF) [13]. It is considered a renewable energy source. RDF is rarely used on its own, instead most commonly co-fired with other solid fuels (e.g., coal or biomass pellets) by large industrial plants, with cement plants as a common example used in case studies [13–17].

In Poland, RDF is typically produced by mechanical–biological treatment plants from municipal solid waste using a combination of processes, usually beginning with the separation of fine (mostly organic) particles (<50 mm) from larger ones; the larger ones tend to exhibit properties favorable for energy recovery [18,19].

As refuse-derived fuel is not a homogeneous material (instead consisting of a particulate mix of combustible non-recyclable material, thus inhomogeneous both in the sizes of particles constituting it and in the material any given one of these particles consists of), its properties may depend on a multitude of direct and indirect factors. These factors might result from the origin of a given sample, such as the average composition of the

municipal waste at the location where or when a given RDF sample was obtained [13], or be environmental or internal, such as the amount of bound water per unit of mass at the moment of burning. In particular, it has been noted that RDF samples drawn from different locations or at different seasons of the year may exhibit differing characteristics, which negatively affects their reliability as fuel [13–17,20]. Such inhomogeneity may result in different performance of RDF-firing facilities, dependent on the properties of a given fuel sample, which in turn can influence the wear of the machines and the performance of the entire process. Homogenization of the material is therefore favorable for purposes of its practicality as fuel. If possible, it is achieved by milling and pelleting, which also carries the added benefit of increasing the bulk density, a property the RDF is known to exhibit at a remarkably low level compared to other solid fuels [20].

An RDF-producing facility may not always receive waste material produced immediately beforehand, especially if it receives waste drawn from landfills; likewise, already processed RDF may also be kept in storage for an amount of time until it is used for energy production. Finally, storage itself can be employed as a means of homogenization (i.e., through the mixing of the material procured at different times for a reduction in the seasonal variance of properties). All of these, however, may themselves result in a divergence of the properties of the material from their optimal or expected values as it cannot be presumed that such material is at all times stored under carefully maintained conditions to limit exposure to elements and the potential decay of the desired properties. At the same time, the careful monitoring of storage conditions may require facilities (e.g., large, air-conditioned warehouses) too expensive (and possibly also politically questionable for the same reason) for the economical storage of RDF. On the other hand, open-air storage exposes the stored RDF to air moisture or rainfall, which may significantly increase the amount of water contained in a freshly drawn sample, as well as wind and other conditions. Exposure to the environment can result in the degradation of stored material. In the case of non-biological, non-ferrous matter, this may involve processes of the wind dispersal of light surface particles, leaching by rainwater, or the decomposition of exposed particles through the effect of sunlight and daily and yearly temperature cycles. Therefore, a discussion of potential changes in the properties of RDF caused by long-term open-air storage is warranted.

This paper presents an assessment of the quality of samples of refuse-derived fuel in regard to the conditions and duration of its storage to test for the possible impact of environmental conditions compared to fresh material and between fractions of various exposures within the source material. The material from which the samples were derived was drawn from a pile stored outdoors for a period of over three years, fully exposed to weather conditions for the entirety of that time. The samples were taken from different depths of the pile in order to assess any potential differences between the more exposed and less exposed fractions of the material. Particle size distribution, bulk density, water content, heat of combustion, and linear expansion over time of a pressed pellet were all measured for this purpose. At the end, the implications of the findings in the context of the storage and use of stored RDF are discussed.

2. Materials and Methods

The RDF pile from which the samples were taken was originally supplied by a local MBT (mechanical–biological treatment) plant in Kraków, Poland, and was delivered to its current location in 2018 [13]; by the time the analyses described in this paper were performed, it had spent three years in open-air conditions. The pile was stored directly on the ground (concrete pavement) and was not covered, thus it was directly exposed to the environment. Figure 1a,b present two photographs of the pile at the time of drawing the samples.



(**a**) (**b**)

Figure 1. Two photographs of the pile taken during the procurement of samples: (**a**) the pile, partially covered in vegetation, photographed while standing near its edge; (**b**) a hole dug to access the deeper layers. The form and composition of the constituent material can be observed.

The primary component (over 70%) of the refuse was found to consist of various unrecyclable plastics, which were followed by textiles and paper, wood and other combustible biomass, and incombustible and unrecyclable matter such as fragments of ceramic or dirt [13]. Once the mechanical and thermal properties of the constituent material were assessed [13,14,20,21], the remainder (amounting to the "oversize fraction" in [13]) was left in open-air storage (upon a concrete floor) as a pile measuring ca. 1.5 m at its tallest point, which remained outdoors following delivery.

The samples were taken on a warm but moist day at three different depths to test for potential inhomogeneities caused by differences in exposure, the effects of leaching, etc. In order from top to bottom, these were from the surface of the pile (as the part of the pile most exposed to the elements); from a depth of ca. 1 m (that depth was assumed far enough from the surface yet still removed from the ground); and from the bottom, where the pile was in contact with the ground; the overall intention was to draw samples from two vertical extreme points (at the top and at the bottom) as well as "from the bulk", i.e., removed from either extreme. The latter two were obtained by digging a vertical shaft into the pile, while the former was simply collected from the surface. For the sake of simplicity, this paper will subsequently refer to the resulting three sets of samples as (in the order of the description above) the surface fraction, the deep fraction, and the ground fraction. Lastly, before any measurements were undertaken, the RDF material, freshly collected from the outdoors pile, was preliminarily deprived of excess unbound water by storing it indoors (in a plastic bucket placed in an unheated but enclosed hall) for 24 h.

The parameters that were subsequently measured were bulk density, water content, ash content, the heat of combustion, and the expansion coefficient of the pellets. The assessment of these parameters is standard in the research of solid fuels such as RDF: bulk density is directly related to the amount of energy stored in the fuel, as well as being important for storage; water bound in a solid fuel lowers the effective amount of energy extracted from firing the fuel (as well as influences the composition of fumes); and ash produced during firing must be disposed of and can potentially clog or chemically damage the furnace. The heat of combustion is directly related to the amount of heat that can be extracted from the fuel and (in tandem with chemical analysis) can be used to further calculate the higher heating value. The expansion coefficient is a measure of the mechanical stability and durability of a pellet.

Particle size distribution was measured by means of sieve analysis in accordance with PN-EN 15415-1:2011 and PN-EN 15415-2:2012 [22,23]. Sieves of 45, 16, 6.0, 3.15, 2.0, 1.4,

1.0, and 0.5 mm mesh were used, and the material separated into different size fractions was then weighed to a 0.2 g accuracy. The sieves used for this purpose were both woven mesh and the perforated plate (of round and square holes) types. For each fraction, the measurement was repeated five times and the mean values were calculated.

Bulk density was measured in accordance with PN-EN ISO 17828 by filling a container of a set volume and measuring the weight of the particulate material within it to obtain the ratio of its weight to the volume of the container. The same laboratory weight as previously used to assess particle size distribution was also used for this purpose [24]. Ten samples of each of the fractions were weighed to calculate the mean values.

Water content was measured in accordance with PN-EN ISO 18134, using an SML 25/250 laboratory drier [25]. Tinfoil trays filled with a previously weighed mass of the material were subjected to 106 °C for 24 h. The dry mass was then immediately weighed, and the water content was calculated as the percentage of mass lost. Similarly, ash content was measured according to EN 18134:2015 and PN-EN 18134:2016 by subjecting the samples (ceramic trays filled with a previously weighed mass of the material) to 250 °C for 24 h (using a Czylok FCF 7 SM furnace) and comparing the weight of the resulting ash to the initial weight of the researched material [26,27].

In accordance with EN 14918-2009 and PN-EN 14918-2010, the heat of combustion was measured using a KL-12 bomb calorimeter [28,29]. In order to attain samples suitable for the device, the material was initially prepared by grinding in an LMMO-100 laboratory mill. To avoid damage to the mill caused by, e.g., small pieces of durable ceramic or hardened steel, the waste material was scoured by hand and eye, and fragments deemed too dangerous were removed before the material was introduced into the mill. As proper quantitative chemical analysis of the material (which is necessary for such calculations) was not available, a decision was made not to calculate the lower heating value from the heat of combustion and to instead rely on the heat of combustion alone as a reasonable replacement for the lower heating value.

Finally, the waste material left from previous experiments was also used to measure the expansion over time of pellets produced by a laboratory hand press. For each fraction, three pellets were prepared, the lengths of such pellets were subsequently measured over the following weeks and plotted versus time, and expansion coefficients were calculated. Calipers of 0.05 mm accuracy were used to measure length.

3. Results

3.1. Particle Size Distribution

The particle size distribution was calculated from the results of sieve analysis of the samples using the following equation:

$$c_i = (m_i / m_{total}) \times 100\%, \quad (1)$$

where m_i is the total mass of the i-th size fraction and m_{total} is the total mass of the material introduced into the sieve setup. Thus, the percentage value denotes a mass ratio of particles of a given size to particles of all sizes, averaged over the number of all samples of the material of a given type, therefore limiting the errors potentially stemming from a small sample size.

Results of the particle size distribution measurement, averaged over five samples of the material for each of the fractions, are gathered and presented along with all-faction averages in Table 2. The symbol next to the sieve mesh size denotes the shape of the openings (round and square).

Table 2. Particle size distribution of the material.

Sieve Type/Size [mm]	Surface Fraction [%]	Deep Fraction [%]	Bottom Fraction [%]	All-Faction Avg. [%]
o 45.0	51.21	68.95	61.82	60.66
o 16.0	10.08	10.38	12.09	10.85
□ 6.00	17.48	5.84	7.81	10.38
□ 3.15	3.53	2.52	3.00	3.02
□ 2.00	2.11	1.43	1.79	1.78
□ 1.40	1.76	1.32	2.00	1.69
□ 1.00	1.64	1.43	2.13	1.73
□ 0.50	5.68	3.44	4.11	4.41
<0.50	6.51	4.70	5.25	5.49
	100	100	100	100

3.2. Bulk Density

The bulk density was calculated using the following equation:

$$BD = m/V\ [kg/m^3], \quad (2)$$

where m is the mass of the material and V = 0.005 m^3 is the internal volume of the vessel used in the procedure as outlined in PN-EN ISO 17828. The results are presented in Table 3.

Table 3. Bulk density of the material.

	Surface Fraction	Deep Fraction	Bottom Fraction
Bulk density [kg/m^3]	376.08	245.13	291.14

These values result in an average of (304 ± 66) [kg/m^3].

3.3. Water Content

Water content was calculated using the following equation:

$$WC = [(m_I - m_D)/m_I] \times 100\%, \quad (3)$$

where m_I is the initial mass of the sample and m_D is the mass after it has been dried. The resulting mean values and standard deviations are presented in Table 4.

Table 4. Water content of the material.

	Surface Fraction	Deep Fraction	Bottom Fraction
Water content [%]	10.0 ± 1.7	24.9 ± 6.9	11.6 ± 3.4

The water content, as averaged over all samples, equals (15.5 ± 8.1) [%], for a large relative error of 52% caused by the outlying value recorded for the deep fraction.

3.4. Ash Content

Similarly to the above, the ash content of the material was calculated using the following equation:

$$AC = [(m_I - m_A)/m_I] \times 100\%, \quad (4)$$

where m_I is, likewise, the initial mass of the sample and m_A is the mass of the ash left in the tray after thermal treatment of the sample. The mean values and standard deviations of the calculated ash content are presented in Table 5.

Table 5. Ash content of the material.

	Surface Fraction	Deep Fraction	Bottom Fraction
Ash content [%]	23.0 ± 3.7	29.0 ± 8.2	32.8 ± 6.8

As averaged over all samples, the ash content equals (28.3 ± 7.5) [%].

3.5. Heat of Combustion

The heat of combustion of the RDF under research was measured for three samples per fraction and the results were averaged. The mean values of the measured heat of combustion, as well as standard deviations for each, as calculated from these results, are presented in Table 6.

Table 6. Heat of combustion of the material.

	Surface Fraction	Deep Fraction	Bottom Fraction
Heat of comb. [kJ/g]	22.5 ± 1.8	25.5 ± 1.5	24.7 ± 2.6

For comparison, the value of heat of combustion, calculated as an average over all samples, measures (24.2 ± 2.2) [kJ/g].

3.6. Mechanical Properties and Expansion Coefficient

As described in the Section 2, the material used in calorimetric measurements first had to be milled in order to enable the proper preparation of samples. As a side result, it was observed that under the given setup, the material was milled reasonably well; no undesirable effects such as clogging of the mill or melting in the heat generated by friction in the running machine were observed.

For pellet preparation, unmilled material was introduced manually into a laboratory hand press. No milling was found to be necessary for the preparation of pellets in this manner, although care was taken not to introduce metal or hard ceramic fragments into the press. These qualitative observations were then followed with a quantitative assessment of the expansion coefficient of pellets.

The expansion of an RDF pellet was measured over time. The equation used to calculate the expansion coefficient was as follows:

$$R = [(h_{24} - h_0)/h_0] \times 100\%, \quad (5)$$

where h_{24} is the length of a pellet after 24 h compared to the initial length h_0. Since further measurements were taken over the following days, Equation (5) was then modified by substituting h_{24} length with a mean of the full range of lengths measured over time, and the defined averaged coefficient of expansion was calculated as well. The values of the expansion coefficient, averaged over three samples for a given fraction, are presented below in Table 7.

Table 7. Expansion coefficient of pellets produced from the waste material.

	Surface Fraction	Deep Fraction	Bottom Fraction
R (24 h) [%]	4.4	5.8	3.6
R (full) [%]	5.5	5.1	6.2

Taken altogether, the average expansion coefficient for all samples was 4.6% for the period of 24 h and 5.6% for the entire data set.

For a clearer picture of the observed trend, Figures 2–4 present the results of measurements taken over the days following the production of the RDF pellets used in the experiment.

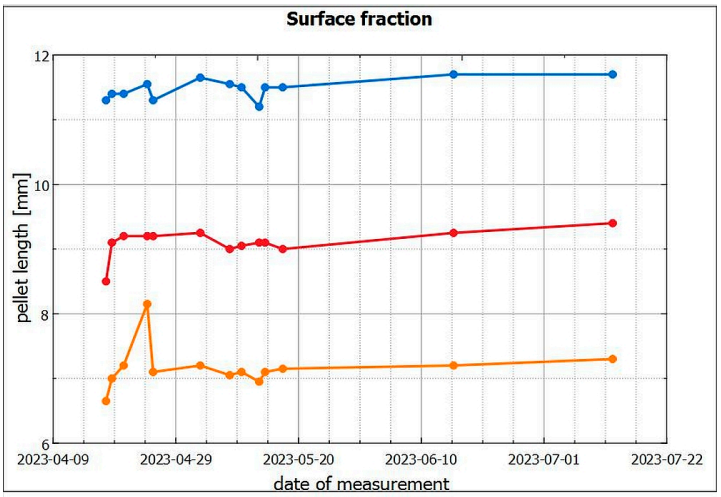


Figure 2. Pellet length measured between April and July for three surface fraction sample pellets. Each of the three pellets is represented by a different color.

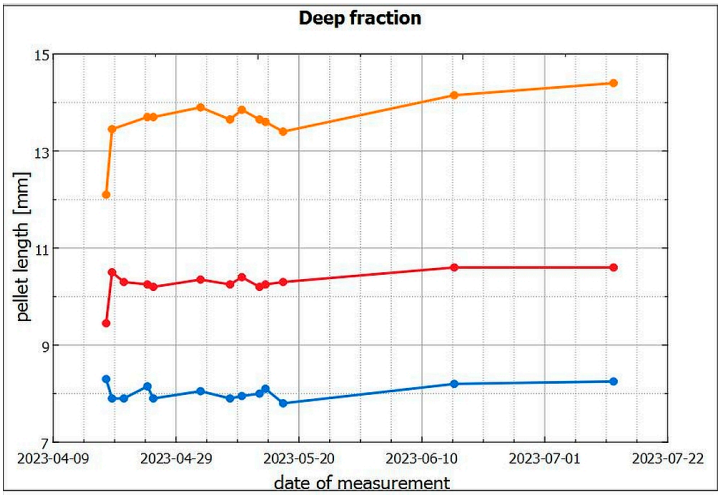


Figure 3. Pellet length measured between April and July for three deep fraction sample pellets. Each of the three pellets is represented by a different color.

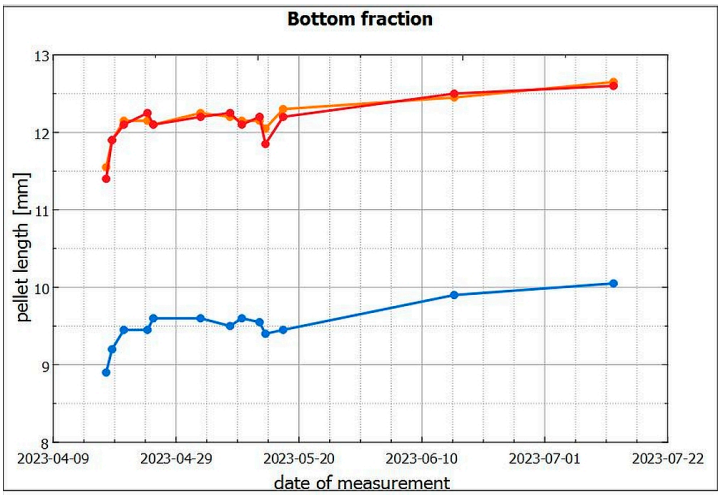


Figure 4. Pellet length measured between April and July for three bottom fraction sample pellets. Each of the three pellets is represented by a different color.

4. Discussion

A comparison of three depth fractions of the material reveals differences in their physical properties. These differences may stem from as far as the initial delivery of the material (dumping from a container), which provided an early opportunity for the partial separation of particles of different sizes and compositions, but also from leaching by rainwater and weathering by wind and other conditions. Due to the amount of material available, it was not possible to perform a large-scale analysis. Nonetheless, the results presented above reveal differences in properties between these fractions.

In regard to other properties, these differences are also noticeable but comparatively to a much smaller extent and/or remain within the ranges of calculated uncertainties. Apart from water content, the spread of measured values is most notable for bulk density, which, however, could be expected from an inhomogeneous mix of various particulate materials such as municipal solid waste where any measurement is heavily reliant on a particular sample. In general, RDF is known for its low bulk density among solid fuels [20]; in the context of depth fractions, the highest bulk density is observed in the surface fraction, which is the most exposed to the environment and can be expected to suffer from the heaviest weathering, breaking up the bigger particles. This is consistent with the distribution of particle sizes, where the smallest percentage of large particles was observed for the surface fraction as well.

In size distribution, the three factions differ predominantly in the amount of large particles, specifically in the 6–16 mm and >45 mm ranges; as the material comprising the "oversize fraction" described in [13], the dominance of large particles confirms the expectations. As the surface fraction contains the lowest amount of the biggest particles, it may be supposed that its heightened exposure to environmental conditions causes these particles either to become dispersed over time (presumably by wind) or broken up into smaller, 6 to 16 mm sized pieces. It stands to reason that the higher amount of smaller particles observed in the surface fraction is the cause of its higher bulk density, as a larger average particle size also means larger average empty spaces between two neighboring particles.

The difference in water content between the deep fraction and the two others is striking even within the bounds of uncertainty, possibly related to rainy weather on the day the sample was procured from the pile. A possible explanation is that the deep fraction samples are drawn from the part of the pile that is the most screened from outside influences, allowing for neither atmospheric drying nor the outflow of excess water. Compared to [13], the deep fraction water content is similar to the previously recorded value of ca. 25.9% (average), while the other two fractions show much smaller values of water content. As mentioned, the samples were stored indoors (unheated) for ca. 24 h before taking the measurements, which provides an explanation for the low water content; this observation offers valuable insight for the design of processes involving RDF use.

The ash content increases from ca. 23% on the surface to ca. 33% at the bottom, with an average value of ca. 28%, close to the previously observed 27% [21]. Higher values observed for the two deeper fractions may come from leaching by rainwater of incombustible particles from the upper to the lower layers of the heap. High ash content in a fuel is undesirable in general, as, among other reasons, it needs to be safely disposed of and may contain significant amounts of heavy metals [12,30]. Compared to the values compiled in [12], which range from 5 to 20%, these results are noticeably higher, which may disqualify the RDF in the presented research from application in certain industries. However, the similarity of the observed values of ash content to those recorded before storage suggests it is not an issue related to storage; conversely, comparatively low ash content in the surface fraction suggests it may be feasible to at least retrieve a part of a stored RDF pile even if its average ash content exceeds the industry limits.

The recorded values of heat of combustion are similar for the three fractions, averaging approx. 24.2 kJ/g. This result is reasonably similar to the previously recorded values of 24.7 kJ/g ("oversize") and 19.9 kJ/g (average) [13,21]. Therefore, the differences in results

are to be attributed to the variance of the material itself, and a conclusion arises that the heat of combustion of the sampled RDF did not change during the period of storage. Of all fractions, the deep fraction appears to contain the most energy. Since it was also found to contain the highest amount of water and almost the highest amount (~29% vs. ~33%) of ash, the simplest explanation remains out of the question. It is possible that the deep fraction consists of particles consisting of materials of the highest energy value, perhaps because particles nearer to the surface and the bottom were partially degraded (e.g., by photo-chemical breaking of polymer chains). However, testing this hypothesis would require chemical analysis, and even if it was confirmed, the differences between fractions remain comparatively small and thus arguably neglectable.

Although the results of the investigation into the expansion over time of a pellet produced from the sampled RDF were heavily dependent on the local shape of the pellet, parallax error, etc., and can thus be only treated as approximate, expansion in the range of 5% (between 4.4% and 6.2%) of the total pellet length was nonetheless noticed. Comparing these results to previous pellet quality assessments such as those presented in e.g., [20], in which a 5% value of the expansion coefficient is assumed to be an upper boundary value for acceptably high-quality pellets, it can be observed that long-term RDF storage is not a concern in regard to the mechanical quality of a pellet.

5. Conclusions

The results of the presented investigation indicate that—in the context of its subsequent processing into refuse-derived fuel and the use of fuel produced from the material stored in such a way, which was the primary object of the conducted research—the long-term open-air storage of municipal solid waste has no notable negative effect on its quality, whether thermal or mechanical. In cases of highly wet environmental conditions, short-term indoor storage was found to be sufficient to remove excess water. As a result, within the contexts provided in this paper, it was found that open-air storage can be safely incorporated into industrial-scale processes of waste disposal and RDF application programs.

In regard to the differences in properties between various depth fractions, some have been noted to be comparatively large, therefore it can be assumed that a large divergence is potentially possible, but in most of the cases observed during the assessment of the researched waste material, these differences did not cause the relevant properties to fall outside of the range of the viability for its use as solid recovered waste fuel. Of the three fractions, the surface fraction appears preferable to the other two on account of having the lowest values of ash content, water content, and expansion coefficient, while also having the highest bulk density; while its heat of combustion is the lowest among the three fractions, that quantity was already noted to change little in comparison to others. This would mark the surface fraction as preferred for drawing the fuel from, but at the same time, it must be remarked that the research presented in this paper could provide no clean delineation between the "surface" and the rest.

A conclusion arises that in cases of very large piles, such as during re-cultivation efforts of waste disposal sites, where drawing material for processing from only a certain depth according to the particular needs of a given waste disposal technology is practically possible, it might be advisable to do so—but otherwise, the observed properties do not differ so much as to make such procedures necessary. In addition, drawing only from the surface would directly hinder the purpose of using RDF as a means to counteract the production of waste. To draw solely from the surface is therefore impractical.

For reasons of time and access to laboratories, this paper omitted altogether any chemical analysis of the RDF, as well as the resultant ash and gases. The authors, however, wish to note that it is an interesting area of further inquiry. An example of such investigations by other authors can be found, e.g., in [30].

Although due to various constraints, the research presented in this paper was limited in scope, several options for continuing these investigations can be suggested. The first of these is to extend the scope: a larger set of samples, samples drawn from multiple

and varied locations, and samples drawn from piles of bigger size. Further, if the size of a pile allows for it, the number of depth categories can be extended beyond the simple surface/deep (bulk)/bottom model presented herein for a thorough study of possible resultant differences in RDF properties. Finally, in the specific context of pellet production, the laboratory method of obtaining a pellet as used in this paper could be replaced with the use of an industrial pelleting machine to account for potential differences between the two methods.

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