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Analysis and Modeling of the Onion Peeling Process in the Blowing Compressed Air Method

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Abstract: This paper presents the relationship between the efficiency of the process of onion peeling and the amount of waste generated in the process. The research was carried out on a pilot test stand for onion peeling. The process variables were the value of the compressed air pressure (p) and the value of the flow opening time through the control valve (t). The experiment took into account the influence of the onion diameter (d_0) and its hardness (H). The obtained results were subjected to statistical analysis. Standard deviations were of the percentage loss of onion mass in the form of the peel removed in the onion peeling process in relation to the obtained average values. Tukey's multiple comparison test was performed in order to identify the importance of individual process variables on the final effect of onion peeling. This was the basis for the development of a predictive model in the form of a non-linear regression $M_p = f(p,t,d_0,H)$, which is a mathematical description of the onion peeling process. Finally, the response surface area of the relationship between analyzed variables was determined. The results of research show that the peeling efficiency of the onion and waste of peel mass depend on the compressed air pressure. Extending the onion blowing time does not improve the process efficiency, while the hardness and size of the onion are irrelevant to the process.

Keywords: onion; peeling; compressed air; peel; waste; non-linear regression

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1. Introduction

The onion belongs to the *Alliaceae* family, genus *Allium*. This group includes over 500 species, the most famous of which are the common onion (*Allium cepa* L.), garlic (*Allium sativum* L.), leek (*Allium porrum* L.), scaly leaves (*Allium schoenoprasum* L.), shallot (*Allium ascalonicum* L.), and seven-year-old onion (*Allium fistulosum* L.). In this group, the common onion is the most popular, with the annual production average in the world at the level of 85–90 million tons [1]. The largest producers of onions are China and India. Their share in world production is approximately 30% and 20%, respectively. In contrast, Europe provides about 15% of the global production [2]. The popularity of onion is characterized by its sensory properties (i.e., its pungent smell and taste, for which essential oils are responsible), and its nutritional and health-promoting values. It is a valuable vegetable rich in minerals (mainly sulfur and zinc), vitamins and dietary fiber. It also contains bioactive compounds with antioxidant properties, i.e., quercetin, kaempferol and anthocyanins (found mainly in red onion varieties), which protect the body's cells against the harmful effects of reactive oxygen species [3]. Therefore, onion has found wide industrial, gastronomic and culinary use. In households and gastronomy, it is used both raw, as an addition to dishes and salads, and is subjected to various types of thermal processing, during which it acquires its additional characteristic taste and aroma. On the other hand, in the food industry, it has been used for the production of dried flakes and powdered middling. It is used for the production of seasonings, soups and sauces. In its unprocessed form, onion is used in canned food, pickled in vinegar, and common in ready meals and frozen vegetable mixes [4]. The beneficial effects of onion on health are also its antibacterial, anti-inflammatory and expectorant qualities and its support of the immune system. Hence, it is used in pharmaceuticals and alternative medicine [5].

A great interest in onion as an industrial raw material resulted in a need for the mechanization and automation of operations aimed at preprocessing onion and its preparation for further stages of production. Knowledge of onion properties is a prerequisite for the design of harvesting and post-harvest machines [6,7]. Sorting operations, cutting the scaly leaves and roots or removing the peel require knowledge of the physical, mechanical and textural features of onion, including its geometric features related to its shape (so-called shape index), size and morphological structure. In the literature, the shape of the onion is defined as elliptical, ovoid, broadly ellipsoid, spherical, broadly oval, rhomboid or spherically flat [8,9]. The shape of the onion is usually modeled as a symmetrical solid with an approximate axis of symmetry passing through the scaly leaves [10–12]. The shape and size of the onion (its diameter ranging from 45 mm to 110 mm) affect, among others, its bulk density, which is in the range of 403 to 716.19 kg/m^3 and which is important for storage and conveyance [6,9,13]. At the same time, it creates the need to segregate the onions for mechanical peeling. The morphological structure of the onion includes a shortened stem (heel), its fleshy leaf (fleshy scales), peel (dry peels), scaly leaf (dried leaf), stalk and adventitious roots [13]. Dry scales and fleshy leaf sheaths adhere to each other but are not fused together, which is of particular importance for the process of removing the peel. On the other hand, the average moisture of onion (unpeeled), affecting the texturizing features, i.e., the crushing force or punching force, ranges from 74.43% to even 90% [6,13,14]. These onion properties seem to be the most important to machine design. Bahnsawy and co-authors [15] showed that the crushing and puncturing forces of the Granex Grano onion are 26.4 N and 25.0 N. Other researchers have shown that the hardness and elasticity of the common onion are at the average level of approx. 13 $\pm$ 2 N and 78.72 $\pm$ 13.78%, respectively [6,13,16]. The puncture strength increases with the onion's size. It ranges from 26.9 to 35.9 N for white onion (variety Giza 6), from 26.1 to 43.0 N for red onion (variety Beheri) and from 27.6 to 45.5 N for yellow onion (variety Giza 20), with the equatorial diameter and polar diameter ranging from 5.17 $\pm$ 0.33 to 6.20 $\pm$ 1.5 cm for all varieties, and their mass ranges from 78.7 up to 115.3 g. Bieńczak and co-authors [17] showed that the cutting force of dried scales of onion ranges from 11.2–14.8 N. Depending on the cutting direction, the cutting force of the onion is in the range of 79.4–97.6 N, in relation to the onion's size. Getting to know the above mentioned properties enables the selection of the process parameters (e.g., the number of cuts and the place of their application) and prediction of the raw material's behavior during the process.

A common agro-industrial practice is to peel onions by descaling and removing the outer, dried layers with the leaf and root part [18]. The dry onion peels are like a papery layer, light brownish and slightly varying depending on the variety. This part contains 11% of all of the onion peeling byproducts, depending on the variety and storage method [19]. The leaf and root parts are strongly attached to the onion bulb and require cutting off, as a result of which a large amount of waste is generated, containing from 30% to 50% of the onion's mass loss. Such a large waste means that the mechanical peeling of onions is only on the edge of profitability. Naik, R. et al. showed that, depending on the variety, the volume of dry peel may contain a maximum of 17.5%, as in the case of Co-3 [20]. Wang L. showed that the total waste from onions can reach up to 25% [21]. On the other hand, Ghanem T. H., in his research, proved that by changing the rotational speed of the drum removing the peel, it is possible to remove up to 12% for the Abo-Fatla variety [22].

These waste products from the purification stage are often revalorized and are a raw material for the production of bioethanol, nitrogen-doped carbon, plastics, biosugar, dyes and other biologically active substances [23–28]. There is an effort to minimize them and reduce food waste. Therefore, these activities are still often performed manually in food processing, despite the continuous development of techniques and technologies of the mechanical peeling of onion. On the one hand, this ensures maximum use of the raw material, but on the other hand, it is quite troublesome for both employees and food producers. The result is manual peeling discomfort, staff shortages and a reduced process efficiency. Manual removal of the peel requires the worker to adopt a specific body posture and perform specific wrist movements. It is physically and physiologically burdensome and even promotes the development of degenerative diseases, e.g., CST (carpal tunnel syndrome) [29,30]. In addition, employees are exposed to the long-term impact of sulfonic acid (sulfenic acid) released during the peeling, which irritates the nasal mucosa, causing burning and tearing up of the eyes.

The methods of mechanical onion peeling in construction and adopted technological solutions do not always meet the expectations of food producers. In addition to a larger amount of waste material compared to manual peeling, these methods are characterized by a high energy consumption and a need to segregate the onions into classes in terms of their size. These solutions do not always comprehensively apply to other operations of onion pre-treatment, i.e., descaling, sorting and several-stage peeling with simultaneous segregation of waste. They usually concern one of the initial stages, for example, descaling [17], removing peel from the bulb or omitting the scaly leaf and root parts [31,32]. According to literature reports, the leading manufacturers of peeling onion machines are manufacturers from China, the USA and the European Union (Polish). The solutions of mechanical onion peeling make it possible to divide the process into two main stages: cutting off the scaly leaves and onion root and removing the peel. The devices presented in the literature perform both of these steps automatically and continuously based on modular systems [1,32]. These devices differ in their construction (the method of horizontal or vertical positioning of the onion, the number and shape of knives cutting the peel and cutting off the scaly leaf and root parts) and the factors affecting the raw material [6,7]. Most research works are devoted to the stage of removing the peel using a drum method. This method is based on rubbing onion bulbs against the rough surface of rotating drums [31]. Rotating brushes are fixed inside the drum [1,32] and the method can be carried out with the simultaneous spraying of water at the onions before the peeling process to soften their surface. In their works, the authors mainly define the relationship between quality, effectiveness, process efficiency and raw material factors, such as the drum rotational speed, inclination angle, degree of filling, air pressure or the presence of water (including water at different temperatures), the size and shape of the onions, onion feed rate, etc. [33–35]. The latest solutions suggest cutting the onion peel and blowing it off with compressed air or water. This solution is characterized by the lack of physical and thermal damage, unlike the drum method, and by its higher efficiency [36]. There is, however, little research on this method; the available reports allow us to classify this process depending on the three ways in which it is implemented. The first method is to cut off onion peels and blow them off, without cutting the ends of the roots and leaves. The second is to cut off the onion scales, blow them off and then cut off the ends roots and leaves. The third one consists of first cutting off the ends of the onion, then incising and blowing off the peel [1,7]. Similar to the drum devices, the authors/constructors focus on determining the impact of the technical solutions and process parameters (e.g., the design of nozzles, their number and distance from the onion bulb, air pressure and feeding speed) on the efficiency of removing the onion peel [1,6,37].

The lack of scientific works on the method of peeling onions does not allow us to clearly determine which features and machine construction parameters have a decisive impact on the process effectiveness. Hence, there is a need to look for new solutions optimizing the efficiency and minimizing the waste. It is necessary to repeat the process, shorten the operating time and thus minimize losses and energy expenditure. The main objective of this research was to determine the impact of compressed air pressure during onion peel blowing and the impact of time on the peeling efficiency and byproducts mass fraction produced. An additional assumption was that the amount of M_p should not exceed 7% of the total mass of the onion before peeling. It resulted from the morphological structure of the purified onion variety and its individual physical characteristics. The study assumed the possibility of the automated peeling of onions with a diameter ranging from 40 mm to 100 mm without prior sorting. The intermediate aim of the research was to check the influence of an equivalent diameter and onion hardness on peeling quality.

2. Materials and Methods

2.1. Plant Material

The research material was the common onion (*Allium cepa* L.), Wolska variety. The raw material came from a regional crop from the Krzysztof Korcz Farm in Daszewice (Po-land). During the cultivation, standard agrotechnical and care treatments were performed, such as irrigation and weed control. The bulbs were cleared of stones and soil residues and free of microbiological contamination (no signs of mold). Onions after 6 months of storage on a heap up to 3 m high in a closed and ventilated room were used for the study. The onions were stored in a well-ventilated warehouse with an air temperature between 2–10 °C and relative humidity between 60–70% (non-condensing). The duration of the tests from the moment of collecting a batch of onions from the producer did not exceed 4 h.

Only those from one storage period were included in the research because the research method assumes the assessment of the impact of changes in key process parameters (pressure and blowing time) on the efficiency and volume of waste. This is important due to the selection of components and devices in newly established and previously used industrial lines and the specification of their limit ranges.

Before starting to peel the onion from its scaly leaves, roots and peel parts, each bulb was weighed (RADWAG PS 4500\C\2 laboratory scale) and then its characteristic dimensions were determined, i.e., the length of the equivalent diameter (on the cross-section) and height measured along the axis of symmetry from the root to the bend of the scaly leaves (electronic caliper with an accuracy of 0.01 mm). In addition, the penetrometer (TR Turoni FT 327, Italy) with a measuring bulb diameter equaling 11.3 mm was used to assess the bulb hardness, as presented in Figure 1, and measured in N. The measurement was made in the onion cross-section.

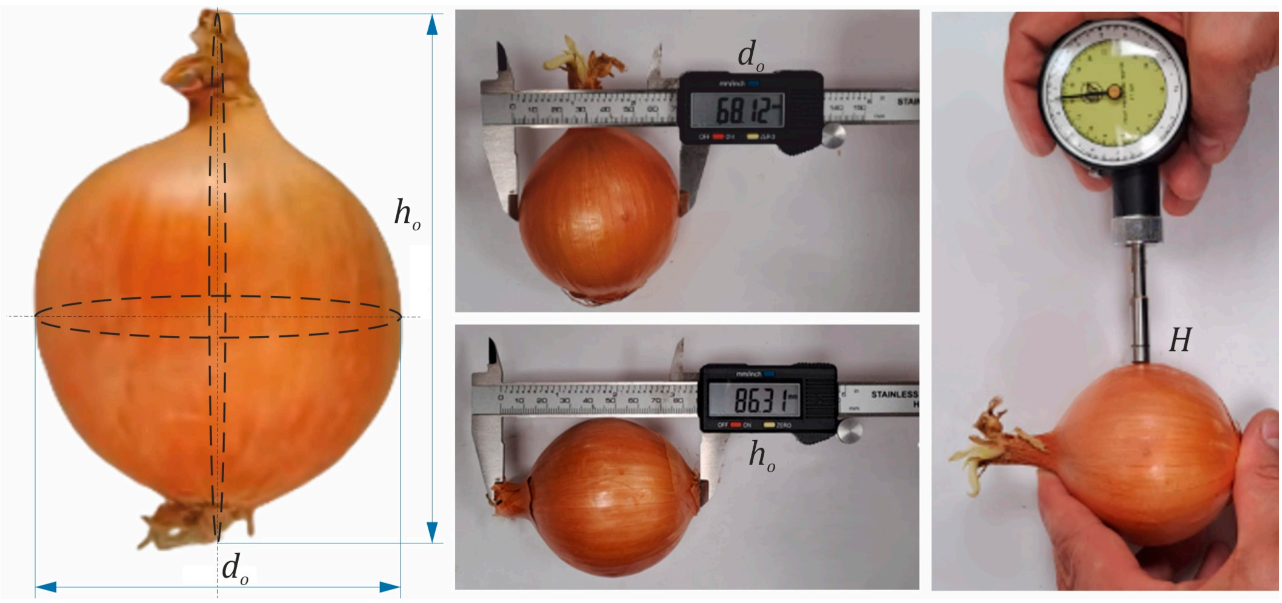

Figure 1. Measurement of the onion's geometrical size (diameter d_0 and height h_0) and hardness with the FT 327 penetrometer.

In regard to Regulation No 1508/2001 [38], onions with a cross-sectional diameter of 40 to 100 mm were accepted for testing. The measurements of the raw material made it possible to classify the onions into the following groups depending on their diameter (d_o): 40–54 mm, 55–69 mm and 70–100 mm and the onion hardness averages (H) were 55 N, 75 N and 85 N. Within the range of the onion bulbs' diameters, the peel percentage for the Wolska cultivar stored for 6 months ranged from 5 to 7% of the onion's mass. The average value for upper and lower limits was determined on the basis of our own research, by peeling 20 onions manually per one process value test.

2.2. The Process of Mechanical Onion Peeling

Onion peeling was carried out on a pilot laboratory test stand, implementing the process in five successive stages, as presented in Figure 2. The main processing stages consisted of removing the root and scaly leaf parts (stage 2), incising the peel (stage 3) and removing the peel layers from the onion bulbs (step 4). In stage 1, it is important to precisely position the onion in a specific position, in this case vertically, where in most machines, it is conducted manually by operators. There are devices available in the world for positioning onions, but they occur only with huge processing capacities.

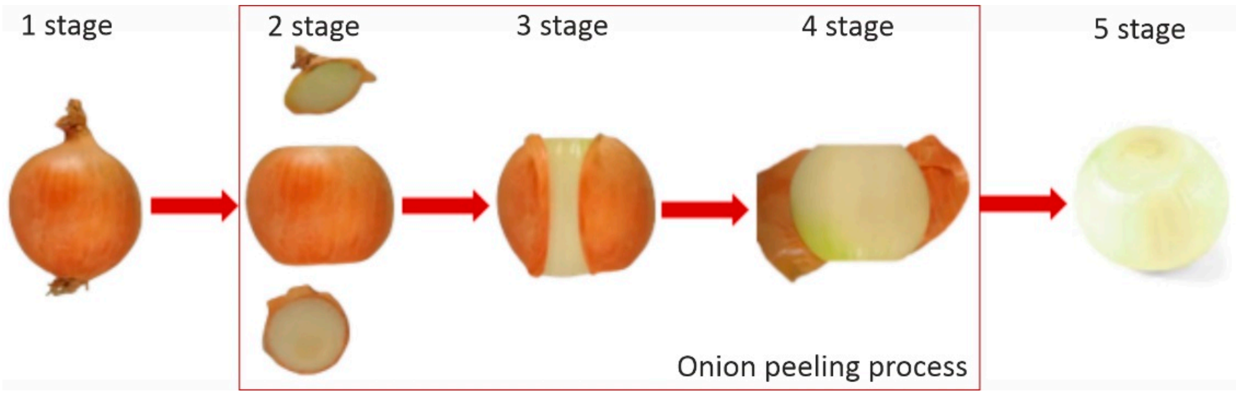

Figure 2. Mechanical onion peeling stages: 1—onion vertical positioning; 2—scaly leaves and roots removal; 3—peel layers incision; 4—peel layers blow off; 5—peeling efficiency control.

The process begins with placing the onion in a socket mounted on conveyor plates, which transported the bulb to the processing systems (stage 1). This stage requires the visual control of an operator and manual correction of the bulb's position in the sockets with a vertical direction, which ensures the accuracy of cutting the root and scaly leaf parts [6,7]. In stage 2, the root and chives are cut off simultaneously and the onion is held in place (locked onion rotation). Cutting is performed with flat or conical knives. In stage 3, the onion peel is cut with the help of 2–4 cutting knives, which allows the peel to be washed off to remove it. Then, the onion is transported to the blowing system. The peeled onion (stage 5) is rated on a hedonic quality scale as acceptable (onions peeled white) and unacceptable (onions containing undesirable elements of peel, creases and damage), as presented in Figure 3. Based on the assessment of the onion's quality after the peeling process, the process efficiency was calculated as the percentage share of the onion with acceptable purity in relation to the bulk quantity.

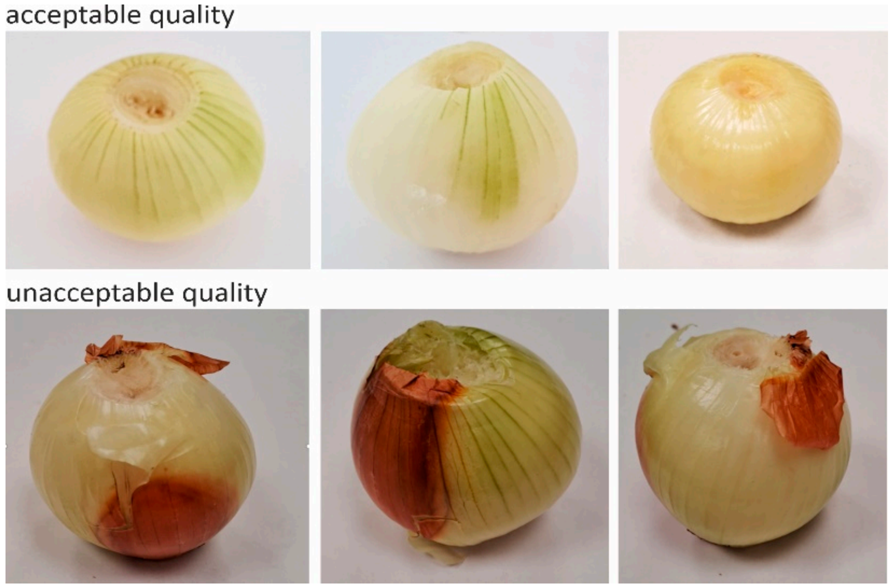

Figure 3. The appearance of the bulbs of acceptable and unacceptable quality.

2.2.1. Cutting System–Scaly Leaves and Roots' Removal

The properly placed onion in the processing sockets is moved to the peeling module. This module includes a cutting unit consisting of a flat onion punch pressing from above and profiled rotating knives mounted in the upper and lower parts of the positioning socket. Another element is specially designed replaceable disc knives, mounted on a four-arm handle. First of all, the upper and lower knives make it possible to cut away the scaly leaf and root parts at the same time. On the other hand, the circular knives cut the peel scales, which, in the next stage, are blown off the onion bulb, as presented in Figure 4.

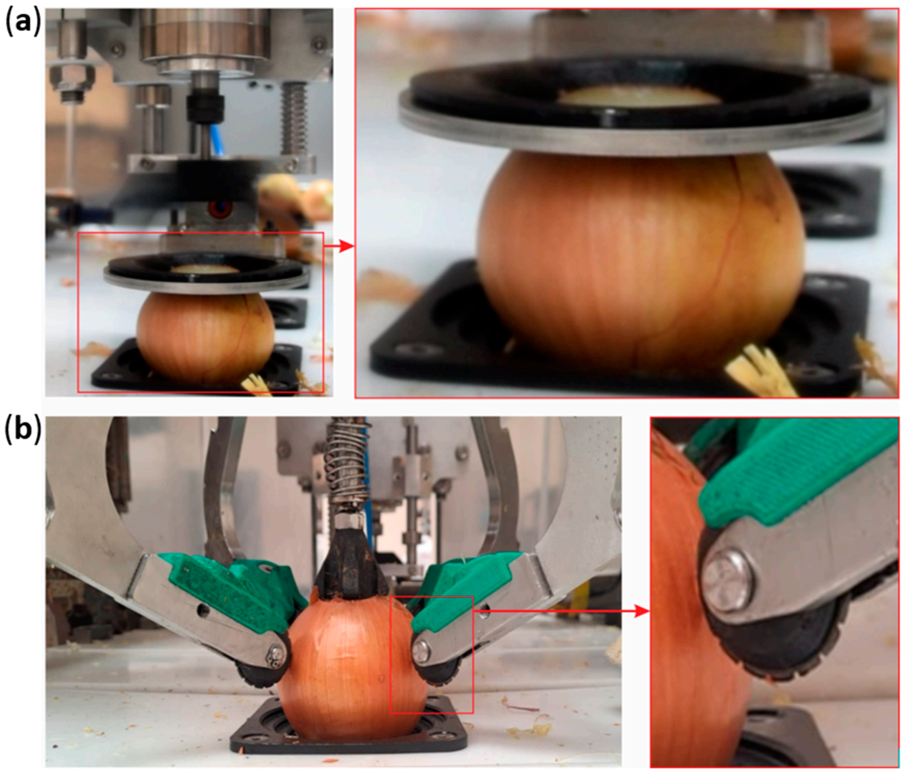

Figure 4. Cutting unit: (**a**)—pressure element with rotating knives mounted in the upper and lower parts in the positioning socket; (**b**)—circular knives cutting the peel.

The pressure of disc blades being adjusted and blade support wheels being replaced (variable diameter) allows us to adjust the system of the onion shape and peel cutting force. It provides control of the incision depth without disturbing wet bulb scales. The process stages were carried out under unchanged conditions and should be treated as auxiliary in the work.

2.2.2. Onion Peel Removal Method

The surface cut of the onion without the scaly leaf and root parts was transported to the blowing system for peel removal. In the module, the onion moves along a discharge chute while rotating around its own axis. This enables the peel to be blown off from the entire surface, as presented in Figure 5. The stage of the blowing off of the peel was carried out using nozzles supplied with compressed air pressure (p): 6, 9 and 12 bar, with an opening time of the control valve to the flow of compressed air set at (t) 0.6; 0.9 and 1.2 s. Basic tests were also carried out for supply pressures of 4–6 bar, which showed a minimum efficiency of 10–20%, taking into account the maximum blowing time. Taking into account the unprofitability of the process, detailed tests were conducted with a pressure value of 6 bar. However, the pressure value of 12 bar was the maximum pressure value that could be obtained on the pilot line, thanks to the use of a pressure amplifier enabling the multiplication of the supply pressure from the industrial line at a level of 8 bar. However, the time values were selected experimentally and above the maximum value of 1.2 s, no significant changes were observed in the onion processing. The rotational speed of the worm shaft moving the onion during the blowing off was set at a constant level of v = 0.035 rpm. In this way, 20 onions were peeled for each variant of variable process parameters.

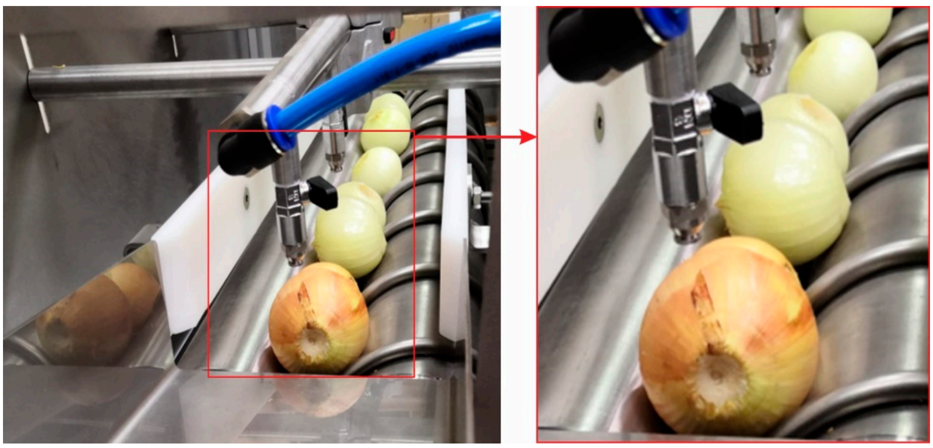

Figure 5. Onion peel blowing unit mounted in the transport chute.

After the process was completed, the treatment efficiency was assessed in accordance with the method described in point 2.2. In the case of the onion peel content, the quality was defined as unacceptable by assigning a value of 0. In the case of onions without peel scales (acceptable quality), the value was 1. The waste in the form of peel was weighed to determine the percentage of mass in relation to the mass of the onion after removing the leaf and root parts.

2.3. Statistical Analysis

Variation ranges for the following factors were adopted in the test plan: compressed air pressure (p) of 6, 9 and 12 bars; control valve opening time (t) of 0.6, 0.9 and 1.2 s; onion diameter in the ranges (d_0) of 40–54 mm, 55–69 mm and 70–100 mm; and onion hardness averages (H) of 55 N, 75 N and 85 N. The adopted ranges of variability of the process parameters resulted from exploratory studies [6] and the onion variety accepted for the study. The observed variables were the peel percentage (M_p) removed at the stage of blowing with compressed air (waste) and the process efficiency (E). The variables were normally distributed. The obtained empirical results were subjected to several stages of statistical analysis in the program Statistica 13, in accordance with the adopted research program for the three-level central compositional plans. In order to check the significance of the examined process parameters' influence (air pressure and blowing time) and the raw material properties (equivalent diameter and onion hardness) on the percentage peel after peeling, an ANOVA analysis of variance was carried out for the factorial systems. The significance of differences between the means was verified by Tukey's post-hoc HSD test at the significance level of $p = 0.05$ [39]. Based on the standardized effects of the Pareto chart, statistically significant factors and their interactions were determined for the stage of peeling of the onion. The analyzed data were presented in the form of a response area indicating the significance or lack of significance of individual impacts. The analysis was carried out both for cumulative effects (acceptable and unacceptable onion purity) and for acceptable effects (100% onion purification efficiency). Statistically significant independent variables determined on the basis of the Pareto analysis provided the basis for adopting the regression function $M_p = f(x)$. This is a predictive model describing the impact of onion peeling parameters by blowing off layers with compressed air on peel percentage waste (M_p). The function was developed using the Gauss–Newton algorithm based on the non-linear least squares estimation in accordance with the method presented in [40]. The adequacy of the adopted models was checked by the goodness of fit of predicted versus observed values, by determining the determination index R and the standard error of Se estimation. The result of these calculations is the response surface between the independent variables and the dependent variable, which enables the determination of the nature of the interactions of individual process variables.

3. Results

3.1. Analysis of Variance

There are several factors to consider when considering the efficiency of the peeling of the onion step. In addition to the peel, the percentage of the process efficiency (acceptable and unacceptable onion purity) is also important.

A statistically significant increase in peel content and 100% efficiency was obtained using a pressure of 12 bar, regardless of the blowing time (0.6, 0.9 or 1.2 s), for all of the variants of the experiment, where the peel value was 9.9–11.7%, as presented in Figure 6. However, at the highest pressure setting, the greatest variation in results (standard deviation) of the technological tests occurred, regardless of the time used.

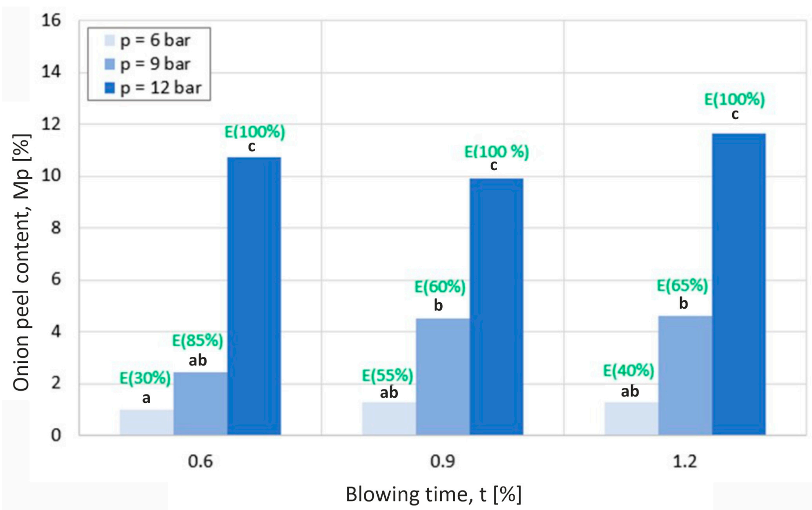

Figure 6. Graph of peel percentage content depending on the variant of the applied pressure and blowing time ($n = 20$, $p = 0.05$; letters indicate homogeneous groups of results within a given parameter), p—pressure [bar]; E—peeling efficiency of onion peel [%].

From the process point of view, the most advantageous selection of parameters seems to be a pressure variant of 9 bar and a blowing time of 0.9 s, at which the average value of waste was obtained at the level of 4.5% and 60% efficiency.

3.2. Determination of the Nature of the Influence of Independent Variables on the Peeling Effect

Figure 7 shows a graph of significance of the level of individual factors' influence in the form of Pareto standardized effects on the percentage loss of onion mass in the form of peel removed. The graphs were prepared for cumulative effects (36% efficiency of the onion peeling process) and for acceptable effects (100% efficiency of the onion peeling process), as presented in Figure 7 [41].

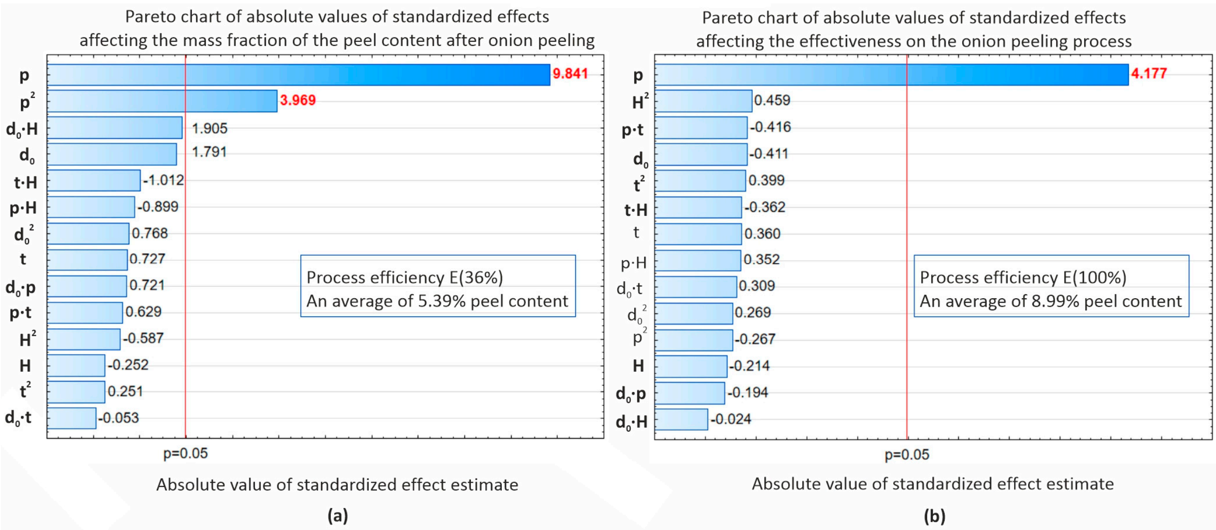

Figure 7. Pareto chart of effects for a quick visual assessment of the significance of input parameters' impact on the % loss of onion mass in the form of peel; (**a**)—for cumulative effects (acceptable and unacceptable onion purity); (**b**)—only for acceptable effects (for the significance level $p = 0.05$). The value of effects above the significance level $p = 0.05$ is marked in red.

A statistically significant factor in the onion peeling process, influencing the amount of M_p (for both analyzed effects), is the compressed air pressure as a linear function (p). Therefore, the influence of this parameter determines the obtained effects. The analysis according to the Pareto test showed that the pressure in the quadratic function (p_2) is also significant, which may suggest the existence of certain extremes of function, i.e., some optimal solutions. In this scope of research, for one variety and one storage time, there are little noticeable changes in diameter (d_0; d_{02}), onion hardness (H; H_2) and the time of opening the control valve (t; t_2), as well as their mutual interactions. The nature of the above impacts is presented in Figure 8.

The obtained response areas indicate that the percentage content of removed peel in the process of peeling the onion (the loss of onion mass) significantly increases with the increasing air pressure blowing. This effect is obtained regardless of the process time and onion properties (diameter and hardness) in high pressures. Assuming that the average peel in the Wolska variety is from 5 to 7% of the total onion mass, depending on the bulb diameter (range of 40–100 mm), the use of high pressures for blowing off layers is unfavorable because it contributes to the increase in raw material losses, as presented in Figure 8. The obtained response surfaces also indicate the range of low pressures, along with the increase in the onion's diameter. It is more advantageous to use a longer blowing time, while the Pareto analysis showed that obtained differences in the content of peel are statistically insignificant. These pressure values decrease the amount of peel, which may be the reason for not peeling the onion. Similar observations apply to an increase in hardness.

In this case, it is better to increase the pressure. Figure 9 presents the post-production waste consisting of removed dry and wet onion scales.

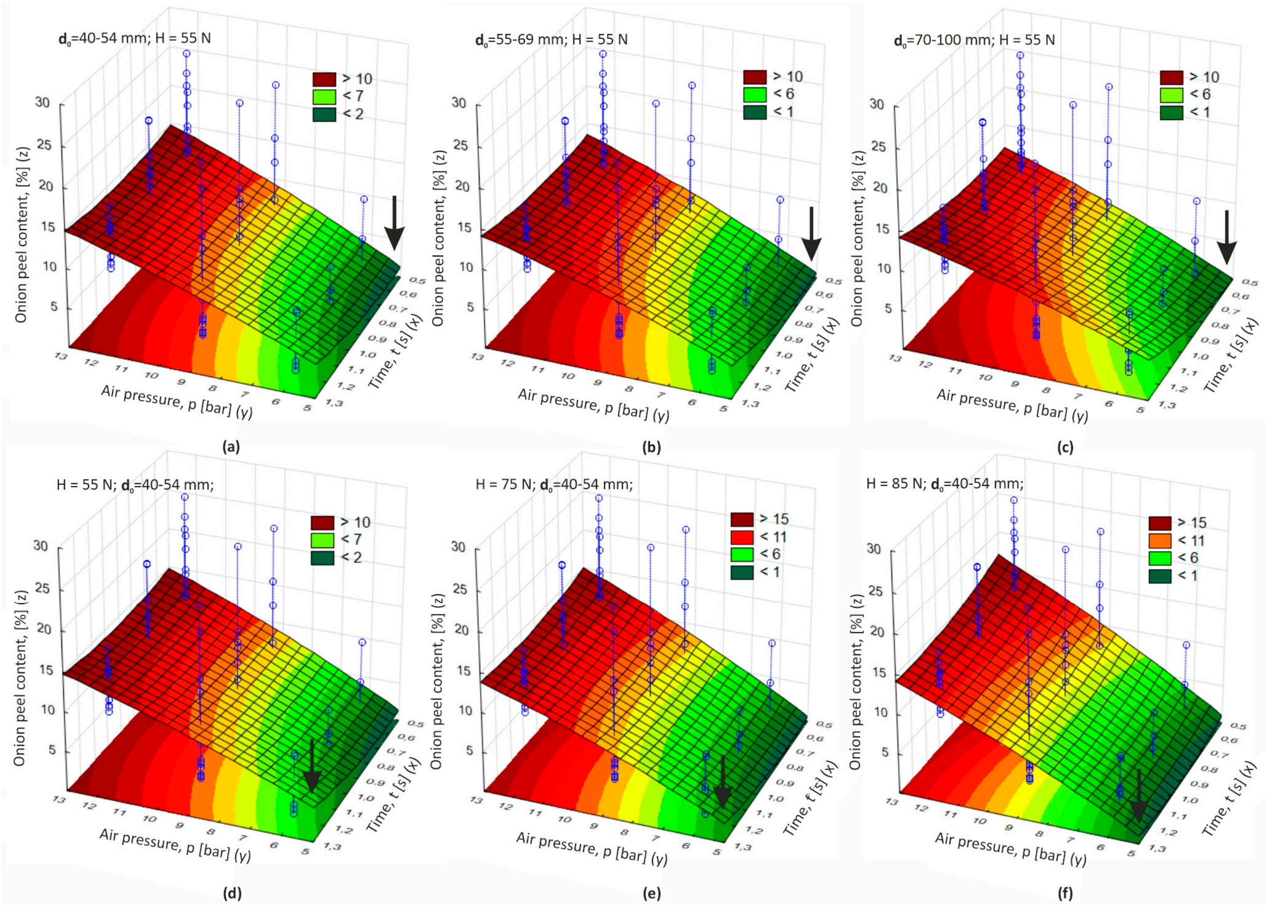

Figure 8. Dependence of peel percentage content removed at the stage of blowing in relation to (**a**–**c**)—substitute onion diameter, indicated by the black arrow; (**d**–**f**)—onion hardness average, indicated by the black arrow.

Figure 9. Waste in the onion peeling process; (**a**)—peel scales after blowing process at 6 bar; (**b**)—peel scales and fleshy leaves after blowing process at 9 bar; (**c**)—peel scales and fleshy leaves after blowing process at 12 bar.

The waste presented above in the form of onion peel removed indicates the dependence of the wet onion layers in the waste on the blowing pressure. In the range of 6–9 bar, the content of wet onion peel is negligible. A significant increase in wet waste is observed when the pressure is increased to 12 bar, which is undesirable due to the formation of significant losses of processed raw material.

3.3. Assuming the Final Predictive Model $M_p = f(t,p)$

Further analyzes were aimed at determining the function of the simultaneous pressure effect and time on the peel percentage value removed in the onion blowing process. A polynomial function was adopted for the description, approximating obtained empirical results, the general form of which is presented in Equation (1). Since the control valve opening time (t) is a necessary condition for the process, this parameter was not omitted in the final equation form, although in the Pareto analysis of effects this factor has been shown to be insignificant. However, the interaction of time with compressed air pressure (t·p) and time as a square function were omitted (extension of time does not significantly affect the assessed effects), which is justified by the Pareto analysis effects.

$$M_p = f(t,p) = (a + p + p2) + t \quad (1)$$

This form of function signifies the onion mass percentage loss in the peeling process, and its efficiency depends only on compressed air pressure (impulse impact of air). However, adopting time in this form is only technically justified. Finally, in the equation, the components with a square make it possible to determine the optimum interaction for a given factor of deviation from nonlinearity and extremes. The linear components, on the other hand, determine the trend of the linear nature of interactions of individual factors on the formed waste mass (2). The determined function takes the form according to Equation (2) and reflects changes in the percentage share of peel waste produced (M_p) in relation to the initial onion mass in the peeling process via blowing under (t) various conditions of compressed air pressure (p).

$$M_p = f(t,p) = (7.311 - 2.823 \cdot p + 0.246 \cdot p_2) + 2.22 \cdot t \quad (2)$$

The determined function is graphically presented in Figure 10 as the percentage response surface of the predicted waste product value.

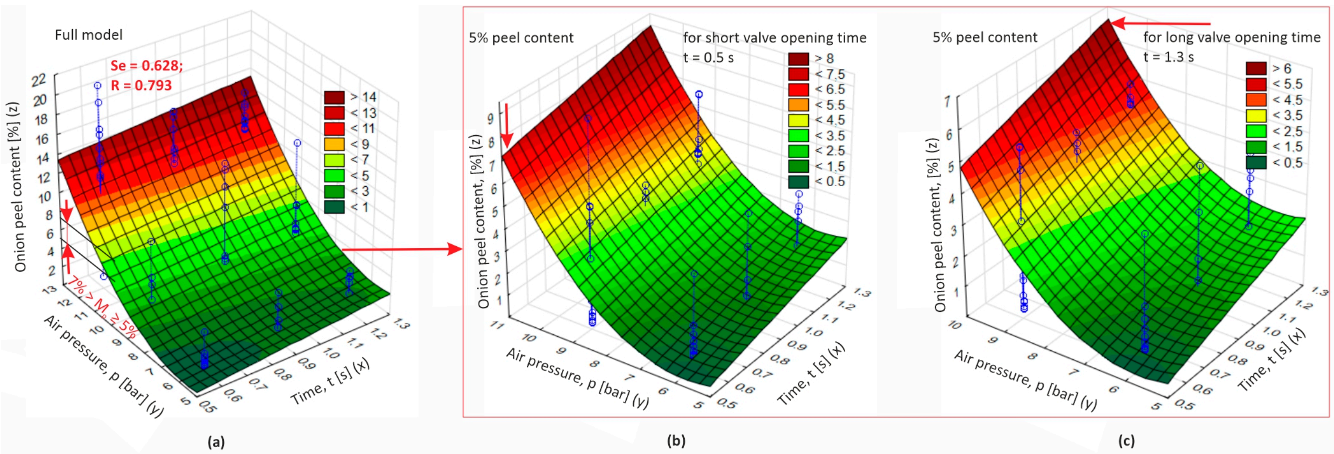

Figure 10. Dependence of percentage content peel removed in the onion blowing process in relation to the opening time of the control valve and the air pressure: (**a**)—response area of observed versus predicted values; (**b**)—response area of observed versus predicted values, taking into account the minimization of waste in the range of 5 to 7% for a short valve opening time t = 0.5 s; (**c**)—area response of observed versus predicted values, taking into account waste minimization in the range of 5 to 7% for a long valve opening time t = 1.3 s.

The goodness of fit of the obtained regression model to empirical data, determined on the basis of the determination index, is high and amounts to R = 0.793. The standard deviation of the residuals is Se = 0.628, as presented in Figure 10. This means that the obtained regression model explains more than 79% of the observed parameters' variables. The average deviation from empirical to theoretical values described by the adopted model is about ±0.63% peel. Based on the obtained response area, it can be assumed that the reduction in losses in the blowing onion process in the form of a peel can be obtained using compressed air pressure in the range of 5–11 bar. Analyzing the process efficiency, as presented in Figure 6 and the fact that the waste peel of the Wolska variety ranges from 5 to 7%, this range for this onion variety after 6 months of storage can be narrowed down to 10–11 bar. It should be expected that the efficiency of removing peel will be at the level of 60–85%, and the generated waste will not exceed 7%.

4. Discussion

This article presents a pilot solution for the technology of mechanical dry peeling of onions. The research concerned the assessment of the impact of process parameters, pressure and blowing time on the amount of waste and the efficiency of manure, which are crucial in onion processing. The basic parameter determining the effectiveness of this method is the pressure in the blowing nozzle supplied with compressed air. However, the opening time of the control valve has a negligible impact on the final result. Therefore, to obtain the desired onion purity and not generate a large amount of waste (in the range of 5–7%), you can assume a compressed air pressure in the range of 10–11 bar. An increase in pressure above 11 bar does not result in higher efficiency but causes significant peel losses above 12% of the total content (above the permissible range of 5–7%). Similar results of the percentage of waste are shown by drum machines for onion cleaning, with values in the range of 6–12%, depending on the drum rotation speed for the Abo-Fatla onion variety [40], and 17–23%, with variable pressure using three blowing nozzles used in post-winter treatment technology [21,42].

Moreover, changing the pressure value from 6 to 12 bar allows for an increase in the efficiency of onion processing, as shown in Figure 6. Depending on the blowing time, the average value ranges from 42% (pressure 6 bar) to 100% (pressure 12 bar). For Giza 6 and Beheri bulbs varieties, the processing efficiency is similar to the studied case, in the range of 55–91.2%, which decreased depending on the efficiency [22], and about 80% in the horizontal technology [21]. To sum up, depending on the solutions used, the processing efficiency of the presented solution is close to the efficiency of ready-made solutions, although none of the others showed 100% effectiveness of peeled onions, even if the waste value increased significantly.

Due to the lack of information regarding the conditions and storage time of the onions tested by other authors, and in the articles which did not also present measurements of the hardness of the tested onions, it is difficult to comment on these parameters. However, the work also includes tests for a narrow range of hardness of Wolska onions, due to the storage period of up to 6 months. To sum up, it is necessary to extend tests for the entire period of bulb storage, starting from bulbs fresh from the field and up to 12 months, in order to verify the impact of hardness on the processing efficiency and the amount of waste generated. An overall period of onion storage will allow verification of the selection of process parameters in terms of production profitability, which translates into the amount of losses caused by the loss of onion mass (waste volume) and the efficiency of the process.

5. Conclusions

The main goal of this work was to achieve minimal product losses for processing efficiency in industrial machines for the mechanical peeling of food raw materials. The presented pilot solution of mechanical peeling technology showed that the efficiency of the process depends mainly on the value of the supply pressure of the blowing nozzle supplying compressed air.

Additionally, regression analysis enabled the determination of a predictive model $M_p = f(p,t)$, the relationship of which is characterized by a very good fit to the empirical data. The values of the determination indices for the determined equation are large, which allows the equation to be treated as an adequate model describing the course of the M_p values. The obtained results of statistical analyses indicate important parameters of this method of epidermis removal. Based on the research results and the discussion presented in this article, it is reasonable to use a pressure in the range of 10 bar for Wolska onions, which represents waste within the range of 5–6% and treatment efficiency of up to 85%.

Since the analyses were carried out only for one onion variety stored for 6 months, it is advisable to extend the research to other varieties with different features (e.g., greater hardness and diameter of the bulbs) and different biological maturity (after different storage periods), including the presented selection and range of parameters. However, the methods and techniques of mechanical processing of onions remain unchanged.

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