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Posted Date: 12 August 2024

doi: 10.20944/preprints202408.0762.v1

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Article

Application of 2D Modification of Hjorth Descriptors to Distinguish Defined Classes of Bee Pollen Images

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Abstract: Adulteration of food products, including honey, is a serious problem in today's economy. Honey has become the third most counterfeited food product in the world, which requires effective authentication methods. This article presents considerations regarding the development of meteorology to test the quality of honey based on the analysis of bee pollen. The justification for conducting such analyses is the relatively high need for the authentication of honey and its derivatives. It turns out that the honey market and honey itself are the third products in the world in which undesirable, inappropriate, and quality-reducing components may appear, affecting the final quality of a product such as honey. The analyses mentioned above thus come down to issues related to the analysis and processing of images. A certain novelty of the approach to this analysis is an attempt to parameterize them using the so-called Hjorth descriptors, which have been a tool known for almost 50 years from the analysis of electroencephalographic (EEG) signals. In this paper, after an introduction to the issues related to testing honey, the issues related to the method of obtaining bee pollen images, improving their quality by applying appropriate filtration, performing normalization, and finally calculating Hjorth distributors such as: Activity, Mobility, and Complexity will be discussed. In the next stage described in this article, the authors perform a detailed statistical analysis leading to the initial construction of a simple classifier that distinguishes defined groups of bee pollen images.

Keywords: bee pollen analysis; hjorth descriptors; food product adulteration; pollen images parametrisation; food product classification

1. Introduction

In the modern economy, honey has become subject to improper labeling and the resulting consequences of falsifying its properties [1,2]. Due to the prevalence of fake honey products, the authentication of honey has become an active area of technical testing of the quality of honey. Among many countries that play an important role in the production market for honey and products derived from honey, New Zealand and the EU countries are the leaders, taking into account the protection of the interests of consumers and producers [3,4]. In the context of the above statement, more and more advanced methods for representing tested products are being sought. Research is usually of an indirect nature; that is, a medium is sought that will well represent the food product while at the same time creating the possibility of using the most advanced information processing technologies regarding the tested feature or the entire product. In the case of analyzing a food product such as honey, properly prepared pollen images or carrying out the so-called pollen analysis regarding pollen

images [5,6]. There is considerable research on the composition and pharmacological bioactivity of bee pollen (BP), indicating its usefulness and safety [7]. Numerous studies have shown that BP has a rich and well-balanced composition to serve as a human food and supplement, while its rich bioactive compounds, especially polyphenols, provide a variety of biological and pharmacological activities [8]. BP-related risks usually come from external factors [9] or from improper storage and processing conditions [8].

Allergic reactions are rare, and BP is perceived as a safe product in most physiological situations, including childhood, older age, and disease recovery [10,11]. BP from different floral sources has been reported to have anesthetic, antiallergic, anti-androgen, anti-atherosclerotic, anticancer (anticarcinogenic and anti-mutagenic), anti-inflammatory, antimicrobial (antibacterial, antifungal, and antiviral), antioxidant, antiulcer, and immunostimulant activities [12]. In metabolic pathophysiology, it has been shown to possess anti-obesity, antidiabetic [13], hypocholesterolemic [14], and hepatoprotective [11] effects. In the digestive system, it has been shown to maintain [10], improve [11], and regulate [14] intestinal functions. In the cardiovascular system, it can reduce capillary fragility [12] and improve overall cardiovascular health [15]. Some authors reported that BP can contribute to the prevention of and positively impact some degenerative processes such as neurodegeneration [15], general aging [13,14], and cellular apoptosis [16], and can promote recovery from chronic diseases and possess chemo-preventive properties [3]. It has also been shown to improve skin health and reparation, including many valuable cosmetic qualities [13].

Due to its established nutritional use, an ISO Norm (ISO 24382:2023) has been published to standardize the quality of bee pollen as a food product [17]. This clear interest in BP is evidently based on a solid background of evidence originating from the ethnopharmacological heritage and increasingly collected experimental data. Although BP in its isolated pellet format may be relatively recent and emerged with the elaboration of mechanical pollen traps, bee bread and plant pollen have been used since ancient times. Ancient Egyptians described pollen as a "life-giving dust" [18], and Greeks believed that pollen and honey gave youth to kings [19]. Pollen was used for cosmetic purposes in ancient China [20]. Ancient Egyptians, Greeks, native Americans, Chinese, and Indians have been reported to have used BP for food and energy on long journeys, as well as for other health benefits [21]. Based on this nutritional and ethnomedicinal history, BP use has been spreading at a very rapid pace during the last few years due to emerging scientific evidence and the extensive development of the dietary supplement market around the world. BP is widely commercialized as a standalone food and nutritional supplement that benefits from its rich and well-balanced composition. The global market is expected to reach around 670 million Euros in 2024 [22].

In this study, we introduce a novel approach to the analysis of bee pollen using Hjorth descriptors [5,6] to create a tool for a relatively simple and reliable classification that distinguishes counterfeit products that lack appropriate metrological characteristics.

The structure of the paper is as follows: in Section 2, we introduce the database of photographed honey samples in (Section 2.1) and the data processing pipeline consisting of data set preparation, normalization and filtration, feature extraction and selection using Hjort descriptors, and classification (Section 2.2). Section 3 presents the results and the summary is presented in Section 4 and Section 5.

2. Materials and Methods

2.1. Materials

2.1.1. Image Acquisition Procedure

The photographed honey sample was prepared as twice-centrifuged honey sediment taken from 10 g of honey. The centrifugation process lasted 10 minutes each time at a speed of 3000 rpm. Before the first centrifugation, the sample was topped with distilled water at 20 ml and then after centrifugation, the liquid above the sediment was removed and refilled with distilled water at 20 ml. After the second

centrifugation, the liquid was decanted and the remaining sediment was mixed and placed on a glass slide.

The photos were taken using a digital camera with a resolution of 5 megapixels, connected to the tube of an optical microscope, the parameter defining the lens magnification was $\times 60$.

Bee pollen was extracted from the photos using a convolutional neural network (CNN). The pre-trained ResNet50 model [23] was used as a base. The ResNet50 model was then trained based on the prepared pollen masks, which enabled it to effectively extract pollen images from honey samples.

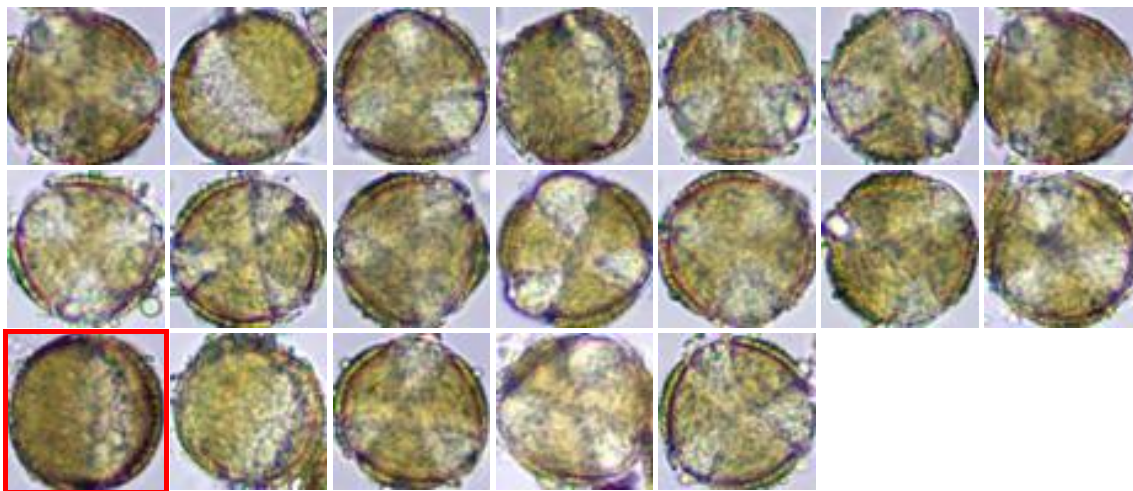
ResNet-50 is CNN architecture that belongs to the ResNet (Residual Networks) family, a series of models designed to address the challenges associated with training deep neural networks. Developed by researchers at Microsoft Research Asia, ResNet-50 is renowned for its depth and efficiency in image classification tasks. ResNet architectures come in various depths, such as ResNet-18, ResNet-32, etc., with ResNet-50 being a midsized variant. ResNet-50 was released in 2015 but remains a notable model in the history of image classification.

The primary problem ResNet solved was the degradation problem in deep neural networks. As networks become deeper, their accuracy saturates and then degrades rapidly. This degradation is not caused by overfitting, but rather by the difficulty of optimizing the training process.

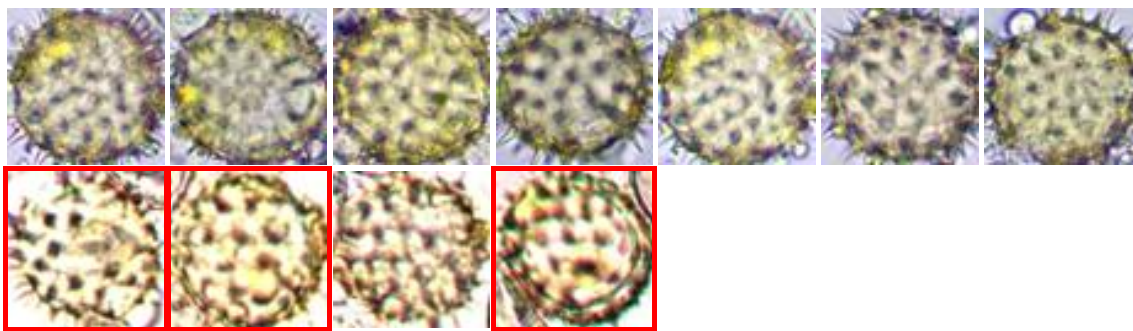
ResNet solved this problem using Residual Blocks that allow for the direct flow of information through the skip connections, mitigating the vanishing gradient problem.

2.1.2. Database

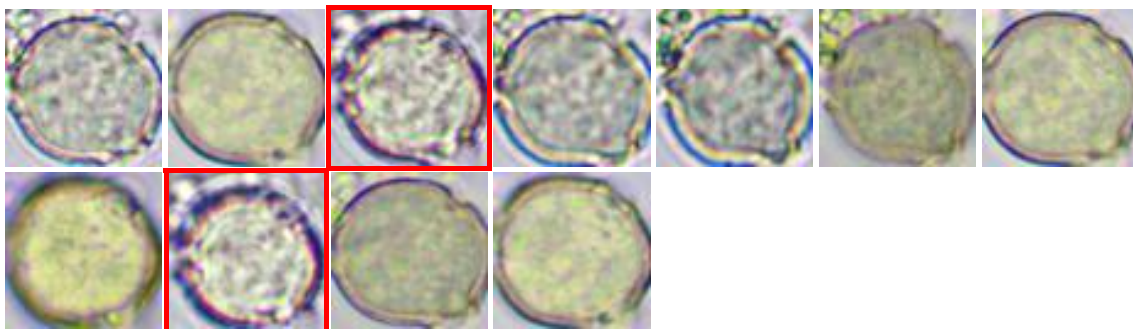
The testing database contained 41 color images divided into three groups: Brassica napus (19 images), Helianthus (11 images) and Phacelia (11 images), each with a resolution of 256×256 pixels and an 8-bit depth. The whole database is shown in Figure 1. In each of the three groups, some images were excluded (images marked in red boxes: Brassica napus 1 image, Helianthus 3 images, and Phacelia 2 images) due to their high mismatch with the group.



(a) Brassica napus



(b) Helianthus



(c) Phacelia

Figure 1. Bee Pollen images divided into three groups (images marked in a red box were excluded from further analysis)

Finally, 35 images (18 images of Brassica napus, 8 images of Helianthus, and 9 images of Phacelia) were used for further analysis.

2.2. Methods

The proposed fully automatic Bee Pollen classification algorithm consists of several steps presented in Figure 2. After the preparation of the database procedure (described in section 2.1) images are subjected to a Normalization & Filtration stage. Then, Feature Extraction & Evaluation procedure is implemented. Finally, based on extracted features, image Classification stage is performed.

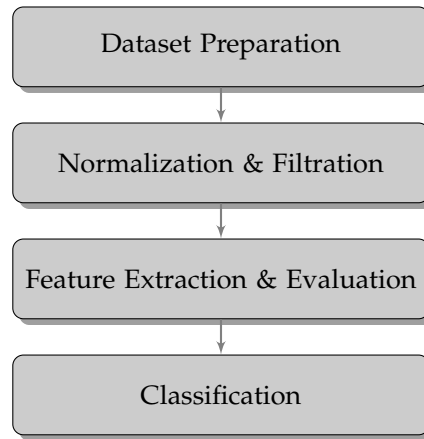


Figure 2. Workflow of the proposed methodology

2.2.1. Data Preparation

Since the numerical analysis uses monochromatic images, the first step is to convert the color RGB images (such as shown in Figure 1) to a grayscale. A grayscale image may be defined as a two-dimensional function $I(x, y)$, where x and y are spatial (plane) coordinates, and the amplitude of I in any pair of coordinates (x, y) is called the gray level of the image at that point. For simplicity, such an image will be denoted as I .

2.2.2. Normalization & Filtration

The next stage after data preparation is intensity normalization and image filtration. The commonly used normalization approach, where the image intensity range gets transformed into the range from 0–1, is a Min-Max normalization or rescaling. It works according to the formula:

$$I(x, y) = \frac{I_{\text{org}} - \min_{I_{\text{org}}}}{\max_{I_{\text{org}}} - \min_{I_{\text{org}}}}, \quad (1)$$

where I_{org} denotes original image. This transformation does not affect the image itself.

Because the derivatives used later are very sensitive to noise, before they are determined, the normalized image is filtered using the average filter. Filter coefficients are calculated according to the average and standard deviation of the image.

2.2.3. Feature Extraction and Evaluation

Further stages of the analysis will use image derivatives. As is commonly known, in the case of 2D signals, the derivative may be directional. However, the directionality of the derivatives in the developed approach is unimportant. For this reason, the gradient modules were determined using combined filters. In the case of the first derivative, the following formula was used:

$$I'(x, y) = \sqrt{\left(\frac{\partial I}{\partial x}\right)^2 + \left(\frac{\partial I}{\partial y}\right)^2}, \quad (2)$$

while for the second derivative:

$$I''(x, y) = \sqrt{\left(\frac{\partial^2 I}{\partial x^2}\right)^2 + \left(\frac{\partial^2 I}{\partial y^2}\right)^2}. \quad (3)$$

For simplicity, the first and the second image derivatives in any pair of coordinates (x, y) will be denoted as I' and I'' , respectively.

The above stages of image preparation and derivative calculation are illustrated in Figure 3. For further analysis, the images presented in Figure 3b–d will be used.

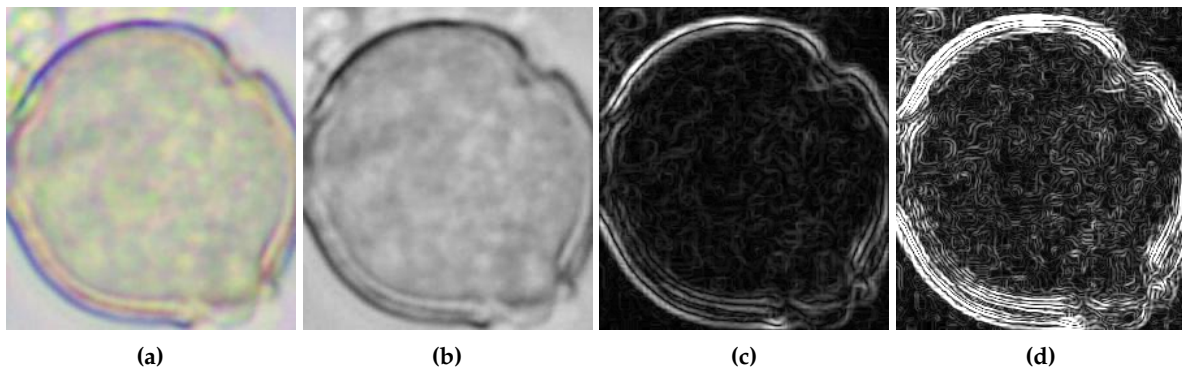


Figure 3. Single data set: (a) original color image (from Phacelia group), (b) original grayscale image I , (c) first derivative I' of the image, (d) second derivative I'' of the image

Hjorth Descriptors

The next step after image preparation, normalization, and filtering is feature extraction and evaluation. In the current submission, Hjorth descriptors were used to extract image features.

The information processing method that uses Hjorth descriptors is a little over 50 years old because, in 1970 [5], Swedish researcher Bo Hjorth proposed the construction of three descriptors: Activity, Mobility, and Complexity to extract classification features and effectively evaluate the EEG signal.

The research using Hjorth descriptors is based on a specific procedure that is relatively typical in terms of recognition and classification issues (see Figure 2).

The EEG signal is, as we know, a one-dimensional signal. Hence, an important novelty in the developed analysis methodology is an attempt to modify the above-mentioned descriptors in order to create the possibility of their application to two-dimensional signals, such as the images of bee pollen being analyzed.

The definition of Hjorth descriptors is derived from the frequency domain. The spectral moment of order n is defined as:

$$m_n = \int_{-\infty}^{+\infty} \omega^n \cdot S(\omega) d\omega, \quad (4)$$

where $S(\omega) = J(\omega) \cdot J^*(\omega)$ is the power spectrum function. This function is computed as the product of the Fourier transform of the signal $I(t)$ described as $J(\omega)$ and its complex conjugate $J^*(\omega)$. The spectral moment of order 0 (zero) m_0 represents the total power of the signal in the frequency domain:

$$m_0 = \int_{-\infty}^{+\infty} S(\omega) d\omega. \quad (5)$$

According to Parseval's theorem [24], the mean power in the time domain is equal to the total power of the signal in the frequency domain, that is:

$$\text{Activity} = m_0. \quad (6)$$

This spectral moment of order 0 is the first Hjorth's descriptors called Activity [25]. The Activity of a signal is defined as the variance of the signal amplitude:

$$\text{Activity} = \sigma_I^2. \quad (7)$$

The dimension of the Activity parameter is the square value of the considered signal. It is worth noting that the variance of a zero-mean signal is equal to its mean power in the time domain:

$$\sigma_I^2 = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T I^2(t) dt. \quad (8)$$

By analogy, the spectral moment of order 2 represents the average frequency of the signal:

$$m_2 = \sqrt{\frac{\int_{-\infty}^{+\infty} \omega^2 \cdot S(\omega) d\omega}{\int_{-\infty}^{+\infty} S(\omega) d\omega}} \quad (9)$$

is known the second Hjorth's descriptors called Mobility:

$$\text{Mobility} = \frac{\sigma_{I'}}{\sigma_I}. \quad (10)$$

And finally, the spectral moment of order 4 represents the bandwidth of the signal:

$$m_4 = \sqrt{\frac{\int_{-\infty}^{+\infty} \omega^4 \cdot S(\omega) d\omega}{\int_{-\infty}^{+\infty} \omega^2 \cdot S(\omega) d\omega} - \frac{\int_{-\infty}^{+\infty} \omega^2 \cdot S(\omega) d\omega}{\int_{-\infty}^{+\infty} S(\omega) d\omega}} \quad (11)$$

is the third Hjorth's descriptors called Complexity:

$$\text{Complexity} = \frac{\frac{\sigma_{I''}}{\sigma_{I'}}}{\frac{\sigma_{I'}}{\sigma_I}}. \quad (12)$$

3. Results

The considerations carried out allowed for the obtaining of the following results, which will be presented in several aspects. First, a collective analysis of the Hjorth descriptors proposed for bee pollen image research was presented to calculate them in an appropriate manner for the three groups of bee pollen and the three descriptors described above (Figure 4).

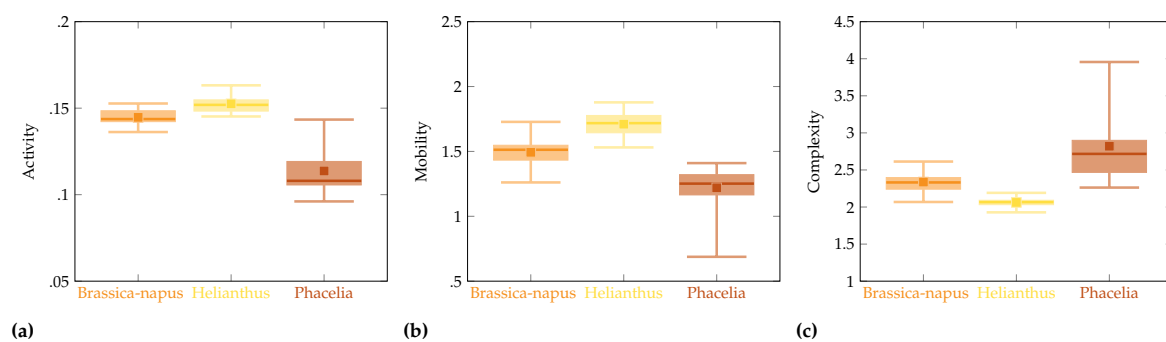


Figure 4. Box plots for Hjorth descriptors: (a) Activity, (b) Mobility, (c) Complexity determined for three bee pollen groups: Brassica-napus, Helianthus, and Phacelia; the box is drawn from the first to the third quartiles, with a horizontal line drawn inside to denote the median and a dot to present the mean; the whiskers indicate the minimum and maximum descriptor's value for the group

This first approach seems to create a reasonable hope of achieving the intended goal, which is a general and independent classifier of bee pollen for their general distinguishability and, subsequently, for checking possible frauds in the production of the final product.

3.1. Statistical Analysis

A statistical analysis has been performed to check whether Hjorth descriptors can distinguish the various bee pollen groups; in our case, the groups are Brassica-napus, Helianthus, and Phacelia. In the first step of analysis, the assumptions of a simple ANOVA test have been verified. Due to the lack of normal distribution and homogeneity of variance, confirmed by the Shapiro-Wilk test and the Levene test (Tables 1 and 2), respectively, and additionally due to the small size of the samples, the nonparametric Kruskal-Wallis ANOVA test, based on ranks instead of measurements, has been applied for the Hjorth descriptors (i.e., Activity, Mobility, and Complexity) representing the bee pollen groups.

Table 1. The smallest level of significance (p-value) for which the calculated value of testing statistic leads to rejection of the null hypothesis of normality distribution and homogeneity of variance for Shapiro-Wilk and Levene tests, respectively for Hjorth descriptors: Activity, Mobility, and Complexity

Hjorth descriptors variable	Normal distribution Shapiro-Wilk test p – value	Homogeneity of variance Levene test p – value
Activity	0.000177	0.001101
Mobility	0.017085	0.031298
Complexity	0.000026	0.000900

p – value (the level of probability p), the smallest level of significance for which the calculated value of testing statistic leads to rejection of null hypothesis

Table 2. The exact results for the Levene test performed for the variance homogeneity of Hjorth descriptors (i.e., Activity, Mobility, and Complexity) to check the assumption of simple ANOVA method of variance analysis

Statistical test	Hjorth descriptors	Effect			Error			F	p
		SS	df	MS	SS*	df*	MS*		
Levene	Activity	0.000395	2	0.000197	0.000744	32	0.000023	8.491422	0.001101
	Mobility	0.079244	2	0.039622	0.327807	32	0.010244	3.867815	0.031298
	Complexity	0.563294	2	0.281647	1.023957	32	0.031999	8.801832	0.000900

SS – sum of squares between groups; df – number of degrees of freedom between groups; MS – mean squares between groups; SS* –within-group sum of squares (residual); df* – number of intra-group degrees of freedom (residual); MS* – mean number of squares within groups; F – F-test value (Fisher-Snedecor); p – value

Kruskal-Wallis ANOVA test assesses whether n independent samples come from the same population (distribution) or the population with the same median (null hypothesis). According to the results summarized in Table 3, there is a significant difference between the bee pollen groups under consideration regarding Activity $p<0.00001$, Mobility $p<0.0001$, and Complexity $p<0.00001$. Based on the results presented, it can be stated that Activity, Mobility, and Complexity have a significant statistical impact on the affiliation of bee pollen to a specific group (Brassica-napus, Helianthus, and Phacelia).

Table 3. The results for the ANOVA rank Kruskal-Wallis test performed for Hjorth descriptors (i.e., Activity, Mobility, and Complexity) obtained for three bee pollen groups Brassica-napus, Helianthus, and Phacelia

Hjorth descriptors	Group	Group size	Rank sum	Rank average	Kruskal-Wallis	
					Test value	p-value
Activity	Brassica-napus	18	348	19.333	21.478	0.00001
	Helianthus	8	229	28.625		
	Phacelia	9	53	5.888		
Mobility	Brassica-napus	18	310	17.222	19.004	0.0001
	Helianthus	8	242	30.250		
	Phacelia	9	78	8.666		
Complexity	Brassica-napus	18	339	18.833	20.944	0.00001
	Helianthus	8	41	5.125		
	Phacelia	9	250	27.777		

Multiple comparison post hoc tests have been performed to answer the question of which of the compared groups is responsible for rejecting the null hypothesis, that is, to indicate which two pollen groups differ significantly. In line with the result obtained (Table 4, Figure 4) for Activity, significant differences have been pointed out between groups Brassica-napus & Phacelia, Helianthus & Phacelia, for Mobility between groups Brassica-napus & Helianthus, Helianthus & Phacelia, and Complexity between groups Brassica-napus & Helianthus, Helianthus & Phacelia.

Table 4. The results (p-values) of multiple comparisons post hoc tests performed for Hjorth descriptors: (a) Activity, (b) Mobility, and (c) Complexity determined for three groups of bee pollen Brassica-napus, Helianthus, and Phacelia; statistical significant differences between analyzed groups are marked with color.

(a) Activity

Group	Brassica-napus RA=19.333	Helianthus RA=28.625	Phacelia RA=5.888
Brassica-napus		0.098529	0.003929
Helianthus	0.098529		0.000015
Phacelia	0.003929	0.000015	

(b) Mobility

Group	Brassica-napus RA=17.222	Helianthus RA=30.250	Phacelia RA=8.666
Brassica-napus		0.008313	0.122515
Helianthus	0.008313		0.000044
Phacelia	0.122515	0.000044	

(c) Complexity

Group	Brassica-napus RA=18.833	Helianthus RA=5.125	Phacelia RA=27.777
Brassica-napus		0.004926	0.097518
Helianthus	0.004926		0.000016
Phacelia	0.097518	0.000016	

RA – Rank average

The separation of individual image groups based on the Hjorth descriptors is also visible in Figure 5.

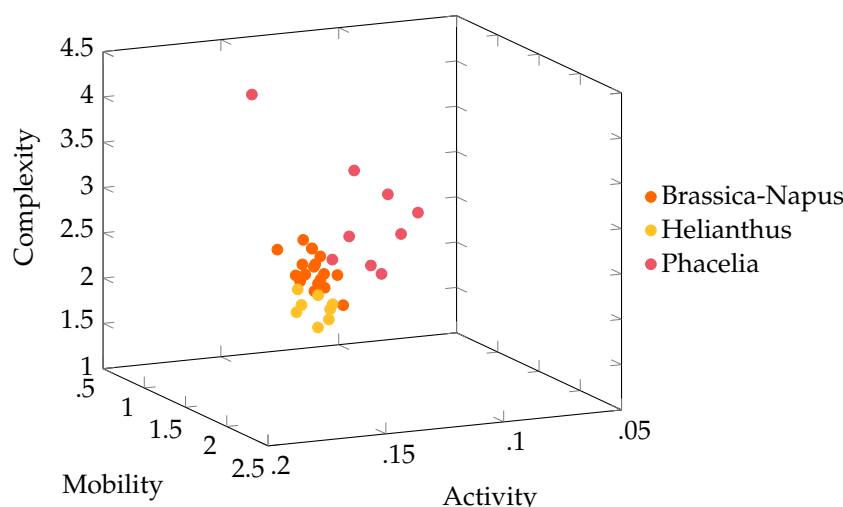


Figure 5. Three-dimensional visualization of analyzed image database of bee pollen three groups represented by points with coordinates of Hjorth descriptors (Activity, Mobility, Complexity)

4. Discussion

This paper presents a novel approach to using the Hjorth descriptor method, known for many years, originally developed for the analysis of one-dimensional electroencephalographic (EEG) signals in the field of analysis of two-dimensional signals, such as bee pollen images. A detailed procedure for acquiring the images mentioned above, which became the basis for the analysis of their discrimination, was described. Therefore, a successful attempt was made to use image parameterization using Hjorth descriptors to construct an initial classifier of bee pollen images.

It should be clearly emphasized here that the primary goal for which such an attempt was made is to introduce some order into the honey production and distribution market, as there are rather chaotic and sporadic attempts to use modern digital tools to make honey production an important element of food product management.

In the paper, intensive statistical analyzes were performed after a detailed description of the tool and the subject of the study, leading to interesting conclusions. Using the descriptors Activity, Mobility and Complexity, it was possible to effectively distinguish the three groups of bee pollen studied. Therefore, appropriate tests of normality of the distribution of the parameters studied (Shapiro-Wilk test) and homogeneity of variance tests (Levene test) were performed. In turn, ANOVA rank (Kruskal-Wallis test) clearly indicated that the listed descriptors in the post hoc test clearly allow for distinguishing the groups of bee pollen described above.

Therefore, to summarize this discussion, it can be stated that a successful attempt was made to parameterize bee pollen images using Hjorth descriptors: Activity, Mobility, and Complexity.

5. Conclusions

The conclusions that emerge from this work can be summarized in two directions. First, in the opinion of the authors, a successful attempt was made to use a somewhat forgotten tool, which seems to be Hjorth descriptors, written for the first time over 50 years ago, to parameterize two-dimensional signals, such as images of bee pollen obtained in the manner described in the methods section 3.1. Second, the use of the aforementioned descriptors, Activity, Mobility, and Complexity, to develop a methodology for distinguishing selected groups of bee pollen images effectively leads to the development of an effective classifier necessary for conducting qualitative analyses of food products such as honey.

The presented approach, although quite effective, has a few limitations. The basic one is the relatively small number of images analyzed in the three groups: Brassica-napus, Helianthus, and Phacelia. Images of these selected bee pollens were obtained through a rather complicated technological process described in the paper. Work is underway to quantitatively enrich the database used for the author's analyses. Then, as can be assumed, performing the analyses described in the article will definitely gain credibility and greater representativeness. The authors of this paper set this as another goal aimed at developing an effective classification tool.

Author Contributions: E.T.: conceptualization, writing and editing; P.R.: image database preparation; W.W.: processing methodology, software implementation, validation, writing and editing; B.L.: image database preparation; B.M.: statistical analysis, results verification, writing and editing, S.S.: writing and editing; All authors have read and agreed to the published version of the manuscript.

Funding: This article was supported by the project program NUTRITECH1/0004A/2022 entitled "Development and implementation of a globally innovative digital honey pollen analysis service using technologies based on automation and artificial intelligence for use in the functional food production sector" selected as part of the 1st NUTRITECH competition – nutrition in the light of the challenges of improving the well-being of society and climate change.

Data Availability Statement: The image data could be provided on request after contact with P.R.

Acknowledgments: The authors would like to express their gratitude to the beneficiary of the competition, that is AI Technika Sp. z o.o., for providing the database of bee pollen images used in the study.

Conflicts of Interest: The authors declare no conflict of interest.

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