Measurement and Information Entropy Theoretical Analysis of Hydrogen Bond Energies in Plant Extracts

Nikolai Neshev[1] Ignat Ignatov[2*] Christos Drossinakis[3]

[1]Sofia University "St. Kliment Ohridski", Faculty of Physics, Sofia, Bulgaria..
[2*]Scientific Research Center of Medical Biophysics (SRCMB), Sofia, Bulgaria.
[3]IAWG- INTERNATIONALE Akademie für Wissenschaftliche Geistheilung, Frankfurt, Germany.

Abstract
Normalized distributions of hydrogen bond energies in 11 medicinal plant extracts were measured with the method of Non-equilibrium energy spectrum (NES). They were analyzed with the information theoretical measures of Shannon entropy and variation of information, as well as with the proposed novel metric of transformational information. Two distinct clusters with respect to these three coordinates were observed corresponding to the common features of anti-inflammatory and immunostimulatory effects and fluoride content.

Key words
Hydrogen bond energy, plant extracts, Shannon entropy, variation of information, transformational information, clustering

*E-mail of corresponding author: mbioph@abv.bg

1. Introduction

Information theory is an interdisciplinary field dedicated to quantification of information. It originated from probability theory, statistics, electronics and communications engineering with the pioneering work of Claude Shannon [1]. Since then, it has been essential for the progress of communication and signal processing technology including coding, detection, error correction, cryptography, data compression, time series analysis, audio and image processing. In addition, information theory has been closely connected with the development of artificial intelligence, particularly with neural networks and deep learning.

Nowadays, the fundamental meaning and powerful methodology of information theory have extended its range towards an impressive variety of other areas, such as: origin of life [2], genetic diversity [3], metabolic networks [4], human vision [5], finance [6], decoding of ancient alphabets [7], geophysics and geology [8, 9], classical and quantum physics [10].

Along these lines, a recent work by van Ruitenbeek et al. used a novel application of the Shannon entropy, being a measure of uncertainty in probability density distributions, to investigate the effects of hydrothermal processes on rock composition. The authors compared the Shannon entropies calculated on measurements of hydrothermally altered rocks with those of their unaltered precursors, including major element compositional data and the short-wave infrared (SWIR) reflectance spectra. They called the corresponding quantities *chemical Shannon entropy* (HCHEM) and *spectral Shannon entropy* (HSPEC) and showed their feasibility as quantitative measures of the effects of hydrothermal processes on the composition of rocks [11].

A similar approach can be applied for analysis of spectral characteristics of hydrogen bonds between molecules in aqueous solutions [12]. Hydrogen bonding is an essential feature of all living organisms on our planet. Theoretical investigations have been performed on processes of life origination in hot mineral water and entropy alterations alongside its evolution [13]. Entropy changes involving polar molecules in hot mineral water from Rupite, Bulgaria were estimated within a model for origin of life [14]. Hydrogen bonds form the double-helix structure of DNA by holding together its base pairs [15]. In addition, they take part in the most common secondary structural elements of proteins —alpha helices and beta sheets. And the unique properties of water due to hydrogen bonding enable living organisms to survive in it even in extreme weather conditions. Moreover, theoretical exploration has been done of chemical and physical properties that could allow for existence of life on other planets, but similarly based on genetic and catalytic molecules. It was shown that functional molecules with genetic and catalytic functions must participate in a hierarchy of chemical interactions taking place in distinct energy bands. Of all known chemical interactions, only hydrogen bonds have the directionality and lower energy that are necessary for genetic and catalytic processes. That is why and also because of the unique quantum features of hydrogen bonding, the molecules that are essential in life processes are predicted to perform extensive hydrogen-bonding [16].
In the present study, we analyzed the distributions of hydrogen bonds energies in a number of plant extracts with the methods of information theory for the purpose of classification and prediction of health effects. These distributions were measured with the methods of Non-equilibrium Energy Spectra (NES) and Differential Non-equilibrium Energy Spectra DNES [17, 18, 19].

2. Materials and methods

2.1. Preparation of plant extracts

Extracts from the following dried medicinal plants were investigated:

- *M. longifolia* L. [20];
- *T. vulgaris* L. [21];
- *S. rosmarinus* Spenn. [22];
- *A. millefolium* L. [23];
- *Tilia cordata* Mill [24];
- *Salvia divinorum* Epling [25];
- *H. perforatum* L. [26];
- *V. myrtillus L.* [27];
- *S. nigra* L. [28];
- *Sideritisscardica* Griseb. [29, 30, 31];
- *Pelargonium sidoides* [32].

The plants were harvested within a particular area of the Blagoevgrad region in Bulgaria and were processed by hot water extraction [33]. For the purpose of the measurements, the extracts were diluted in deionized water in order to obtain standard 1% solutions. *Pelargonium sidoides* is not from Bulgaria.

2.2. Measurements of Non-equilibrium Energy Spectra (NES)

The distributions of hydrogen bonds energies in the aqueous solutions was measured by usingan optical device invented by Antonov, based onthe non-equilibrium process of droplets evaporation [34, 35, 36]. It allows for determination of the Non-equilibrium energy spectrum (NES) distribution, described by a function f(E) where the energy E is expressed in eV.Water drops (10 of a particular sample and 10 controls)evaporated simultaneously on thin mylar foil placed on a glass plate in a hermetic chamber.

The experimental setup is shown in Fig.1. Parallel beams of monochromatic light with wavelength λ = 580±7 nm fall perpendicularly to the maylar foil and the glass plate. Such a configuration allows for measurements of wetting angles in the range from 72.3^0 to 0^0; corresponding to hydrogen bonds energy range E=-0.08– -0.1387 eV. During the measurements, the temperature in the device chamber varies from 22 to 24 ^{0}C.

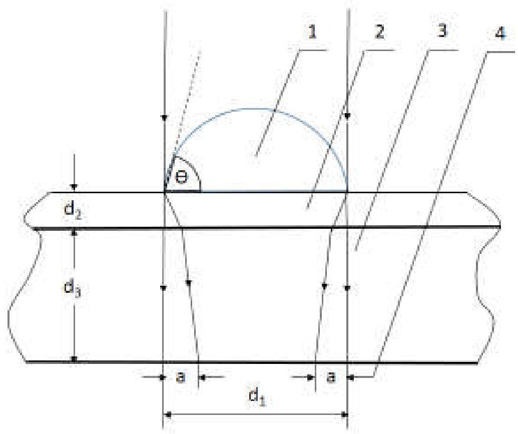

Fig. 1.Measurement of the wetting angle of liquids:

*1-drop, 2 – thin mylar foil, 3 –glass plate, 4 – refraction ring width (**a**). The wetting angle* θ *is derived through measurement of **a** and **d₃***

Throughout the process of evaporation which took approximately 3 hours, the wetting angles of all drops were measured every 10 minutes. After complete evaporation, the average distributions of wetting angles f(θ) were calculated.

Finally, the normalized distributions of hydrogen bonds energies f(E) were calculated as follows [34, 35]:

$$f(E) = \frac{14{,}33 f(\theta)}{[1-(1+bE)^2]^2} \quad (1)$$

where E is the energy corresponding to a particular value of the wetting angle θ, expressed in electron volts. As an example, the Non-equilibrium energy spectrum (NES) of deionized water is shown in Fig. 2.

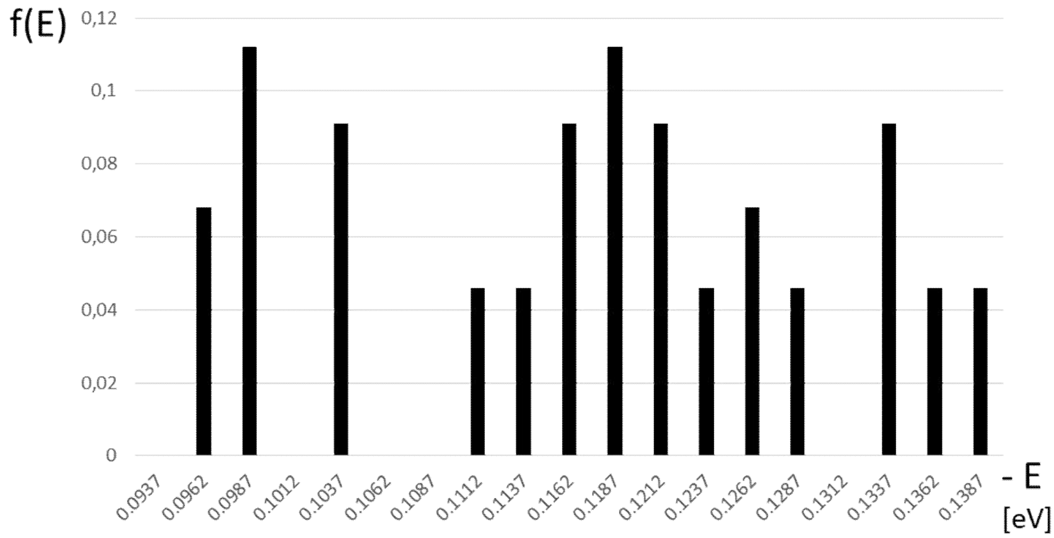

Fig. 2. NES of deionized water

2.3. Shannon entropy

The definition of Shannon entropy (H) of a probability distribution (P) is [1]:

$$H(P) = -\sum_{i=1}^{n} p_i \log\ (p_i) \quad (2)$$

where n is the number of possible outcomes and p_i is the probability of the i-th outcome. In this paper, we have used base 2 logarithms in all relevant expressions, so Shannon entropy is expressed in bits.

As the non-equilibrium energy spectra are probabilistic distributions of hydrogen bond energies, this formalism can be directly applied in their analysis.

2.4. Variation of information

In information theory, the *variation of information* is a measure of the distance between two partitions of elements [16].

If X = {X_1, X_2,…,X_k} and Y= {Y_1,Y_2,…,Y_k} are two partitions of a set C into disjoint subsets, let:

$$n = \sum_i |X_i| = \sum_j |Y_j| = |C|$$

$$p_i = \frac{|X_i|}{n} \quad q_j = \frac{|Y_j|}{n}$$

$$r_{ij} = \frac{|X_i \cap Y_j|}{n}$$

The *variation of information* (VI) between the two partitions is defined as:

$$VI(X;Y) = -\sum_{i,j}^{n} r_{ij}[\log\ (r_{ij}/p_i) + \log\ (r_{ij}/q_j)] \qquad (3)$$

In this study, we calculated the *variation of information* between the NES of each investigated plant extract and the NES of deionized water.

2.5. Transformational information

For the specific purpose of investigating how plant extracts influence the hydrogen bonds and their energies in the solvent (in this case, deionized water), it was necessary to introduce a novel measure called *transformational information* (TI). It can be interpreted as the amount of information necessary to transform the NES of deionized water into the NES of the solution. Its general definition is the following.

If *p* and *q* are probability distributions on a finite set *X*, then:

$$TI(p,q) = \sum_{i \in X} |p_i \log\ (p_i) - q_i \log\ (q_i)| \qquad (4)$$

Whenever *p* and/or *q* are zero, the contribution of the corresponding term is by definition zero because:

$$\lim_{y \to 0+} y \log(y) = 0$$

The *transformation of information* is a true metric because it is a non-negative real-valued function which satisfies the following axioms:

1. Identity of indiscernibles:
$$TI(p,q)=0 \Leftrightarrow p=q$$
2. Symmetry:
$$TI(p,q)=TI(q,p)$$
3. Triangle inequality:
$$TI(p,q) \leq TI(p,r)+TI(q,r)$$

As it can be seen from the above considerations, TI can possibly be applied also in other areas.

3. Results and discussion

The NES graphs of the investigated plant extracts are shown in Fig. 3 to Fig. 13 as black columns, while the NES of deionized water is added to each of them for comparison as white columns.

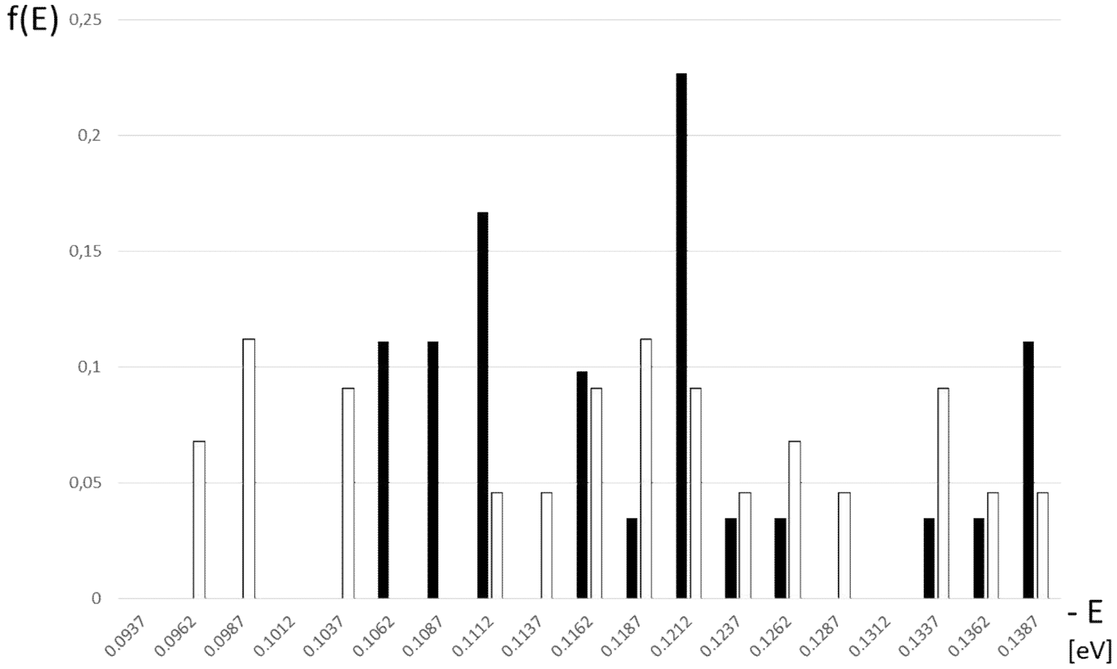

Fig. 3. NES of *H. Perforatum* L.

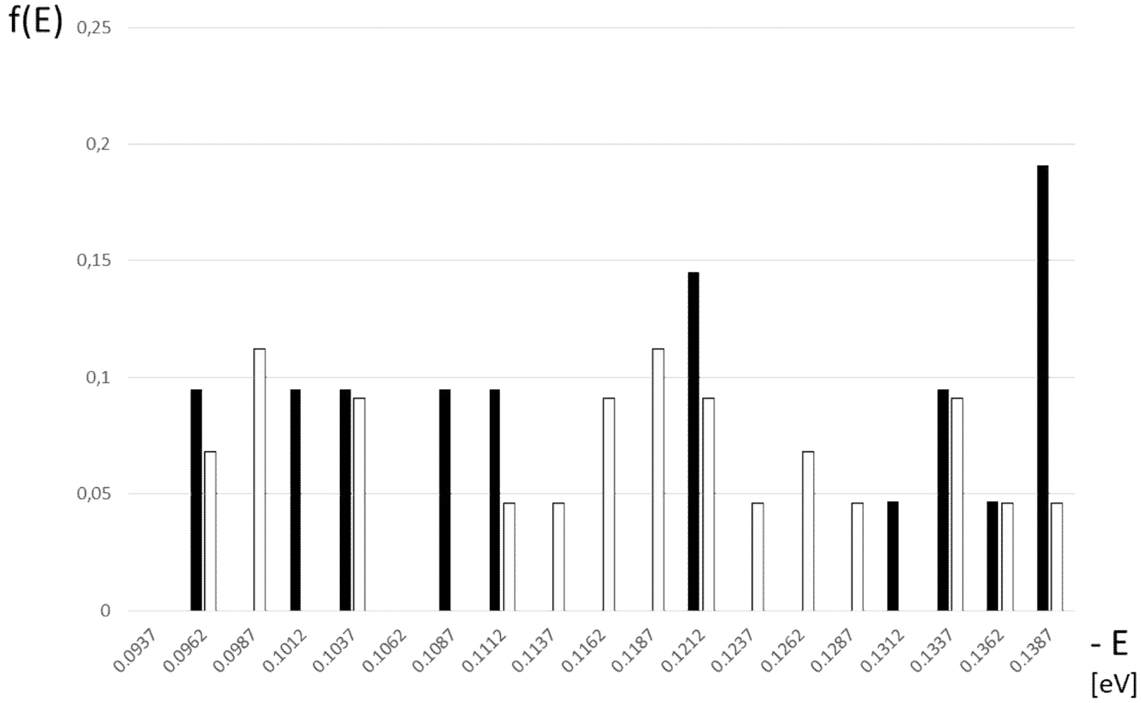

Fig. 4. NES of *M. longifolia* L.

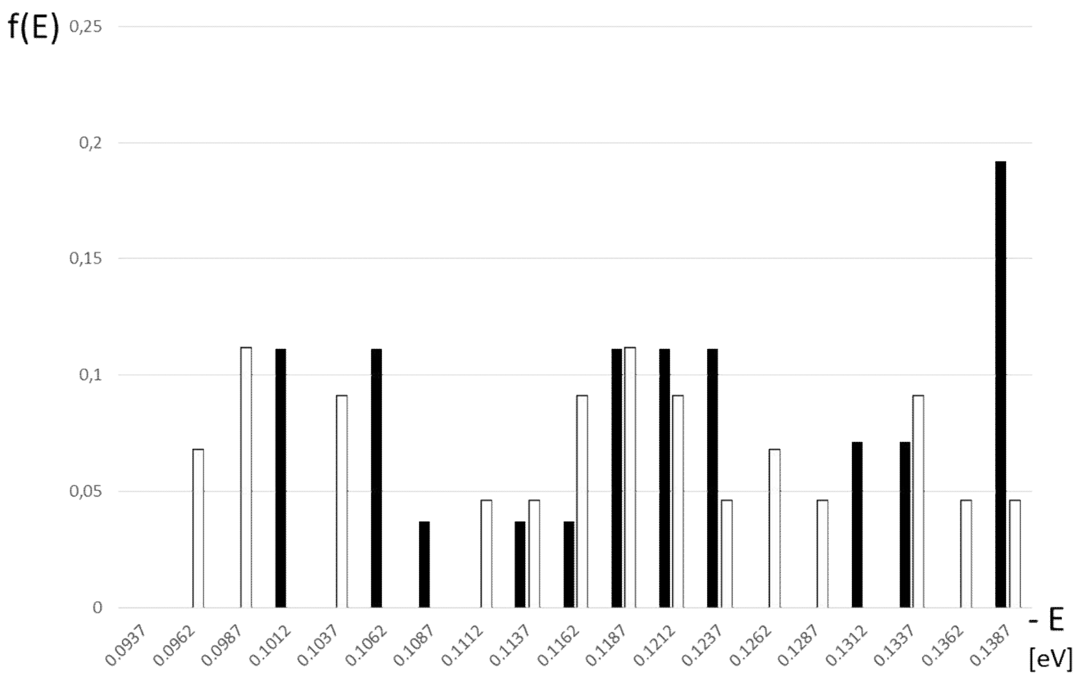

Fig. 5. NES of *A. Millefolium* L.

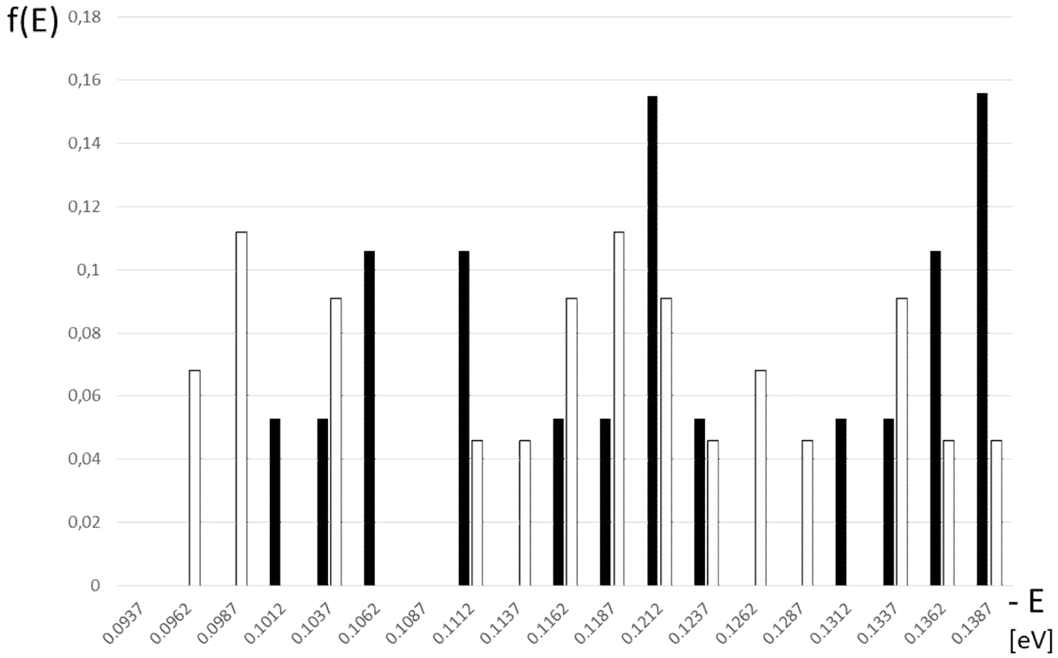

Fig. 6. NES of *Pelargonium sidoides*

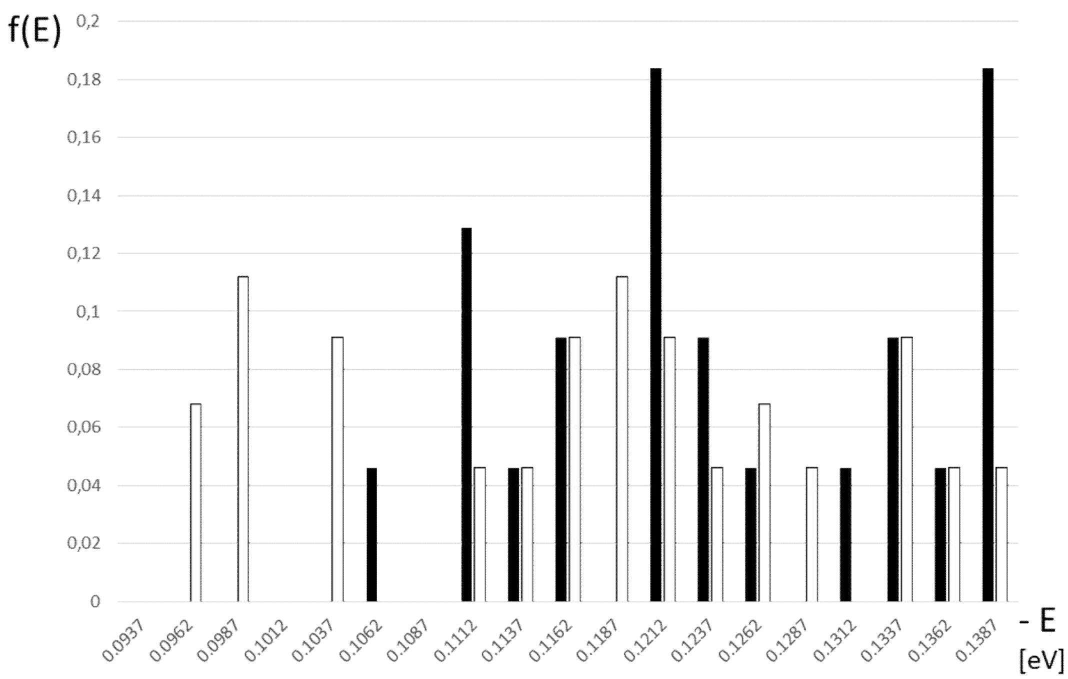

Fig.7. NES of *Sideritis scardica* Griseb.

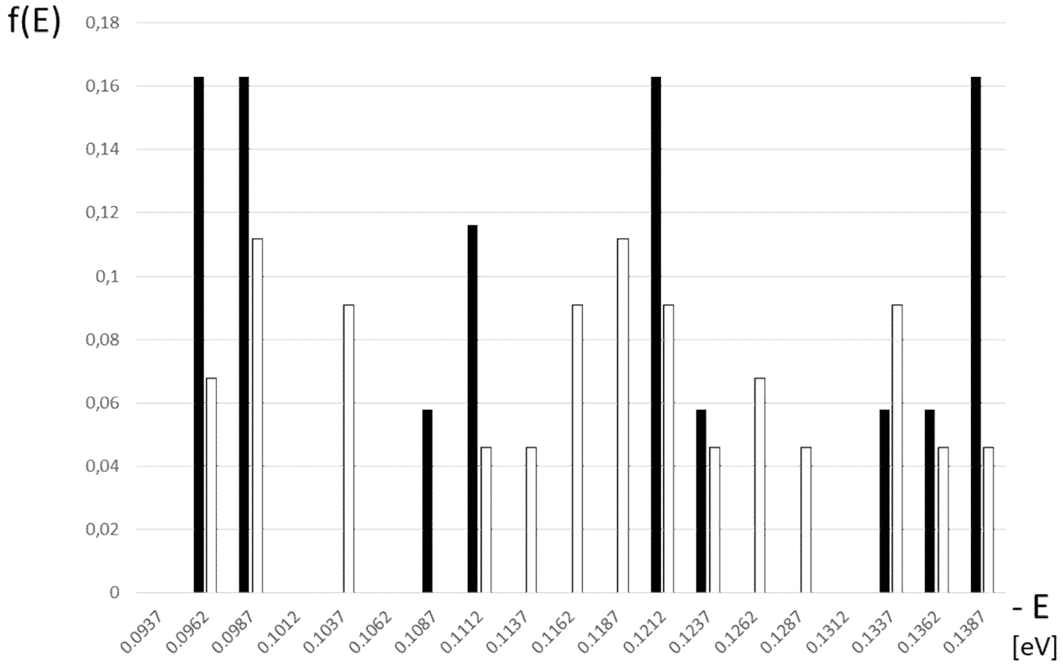

Fig. 8. NES of *T. vulgaris L.*

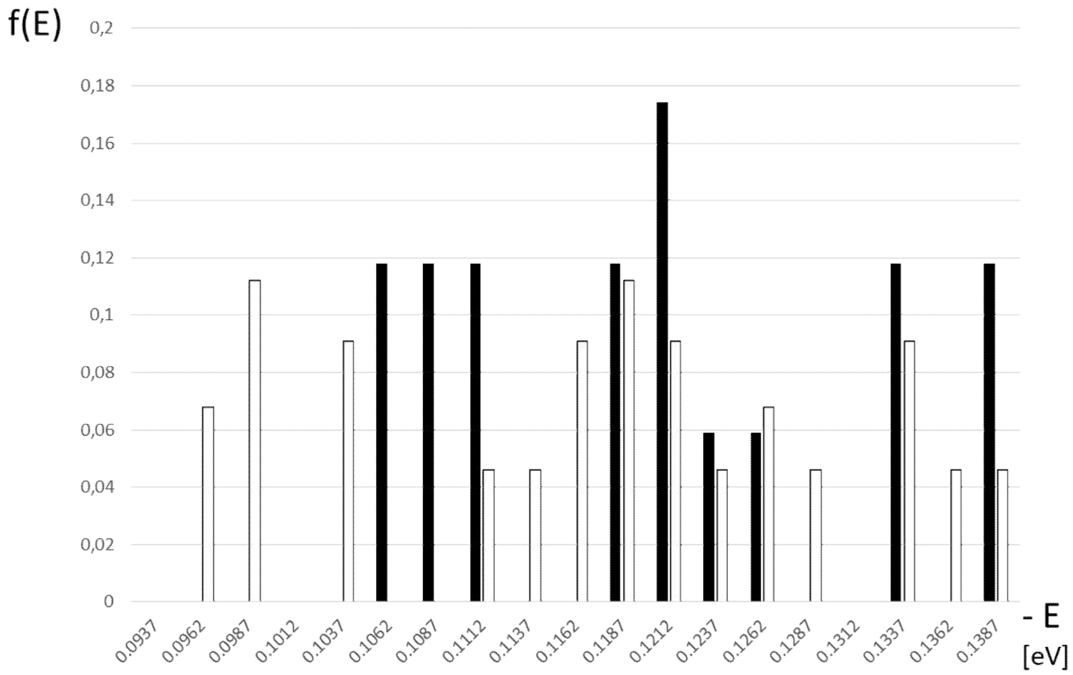

Fig. 9. NES of *S. rosmarinus Spenn.*

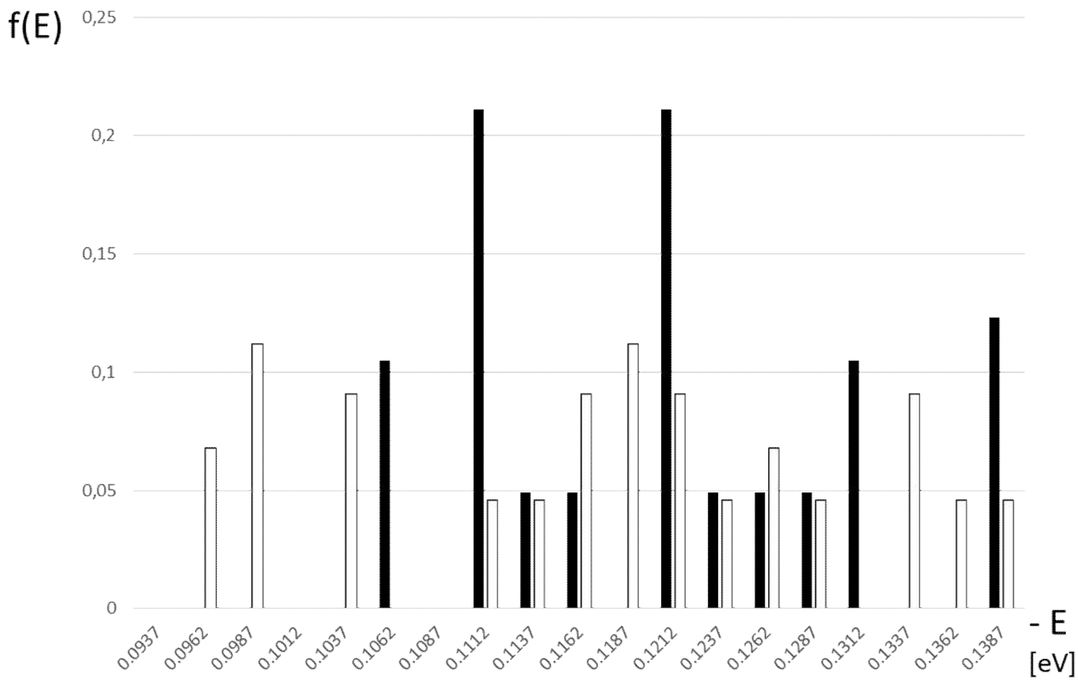

Fig. 10. NES of *Tilia cordata* Mill.

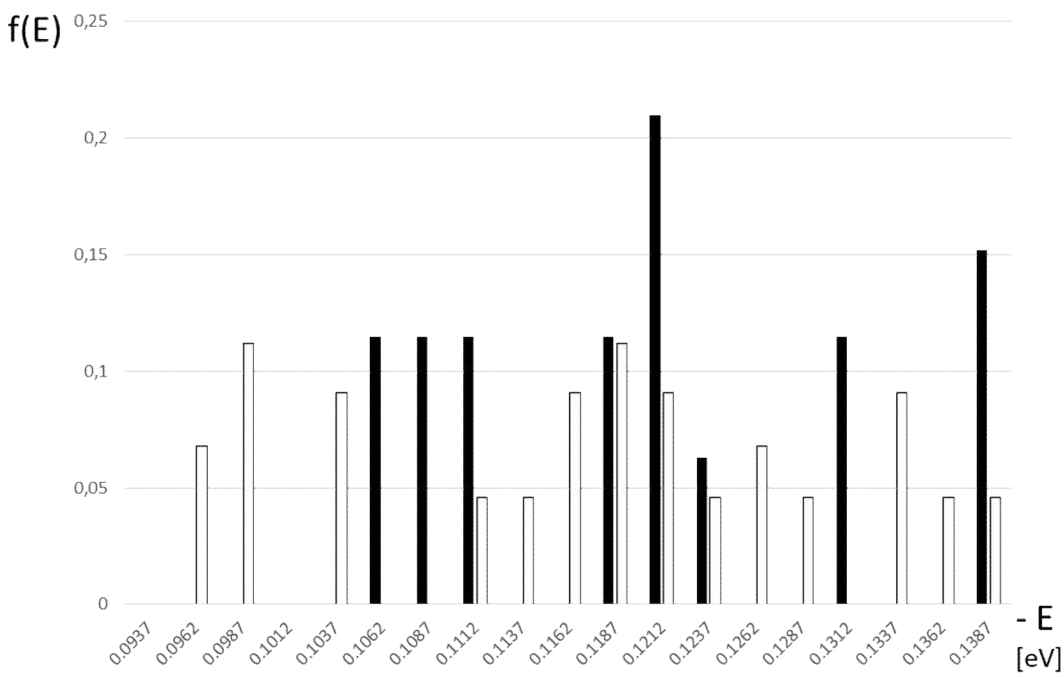

Fig.11. NES of *Salvia divinorum* Epling

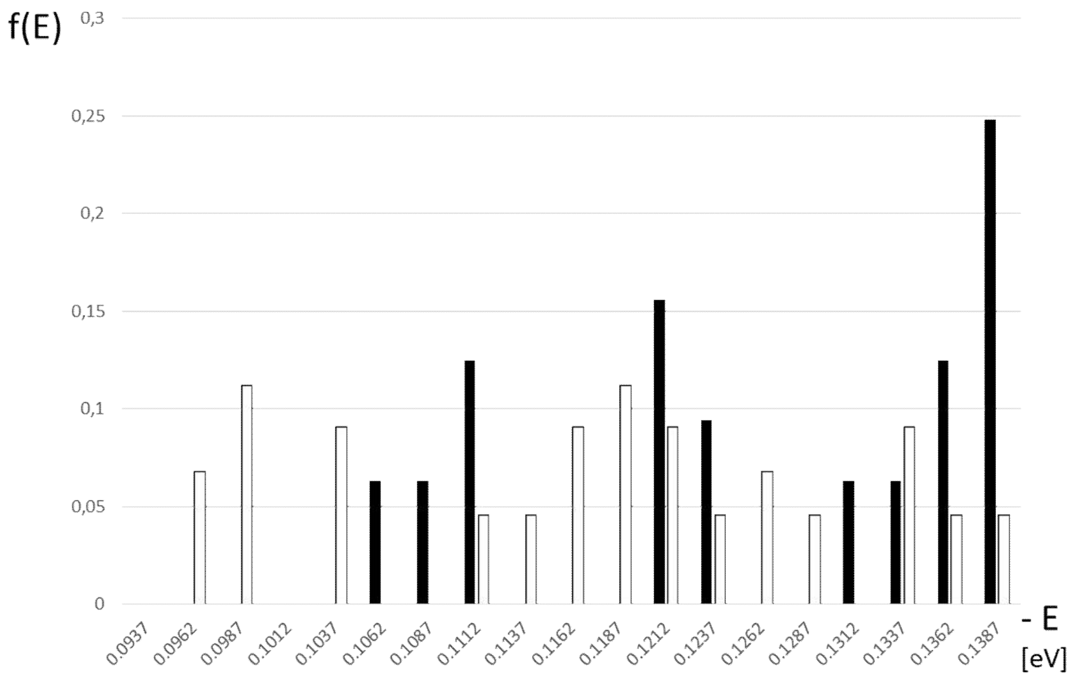

Fig.12. NES of *V. myrtillus L.*

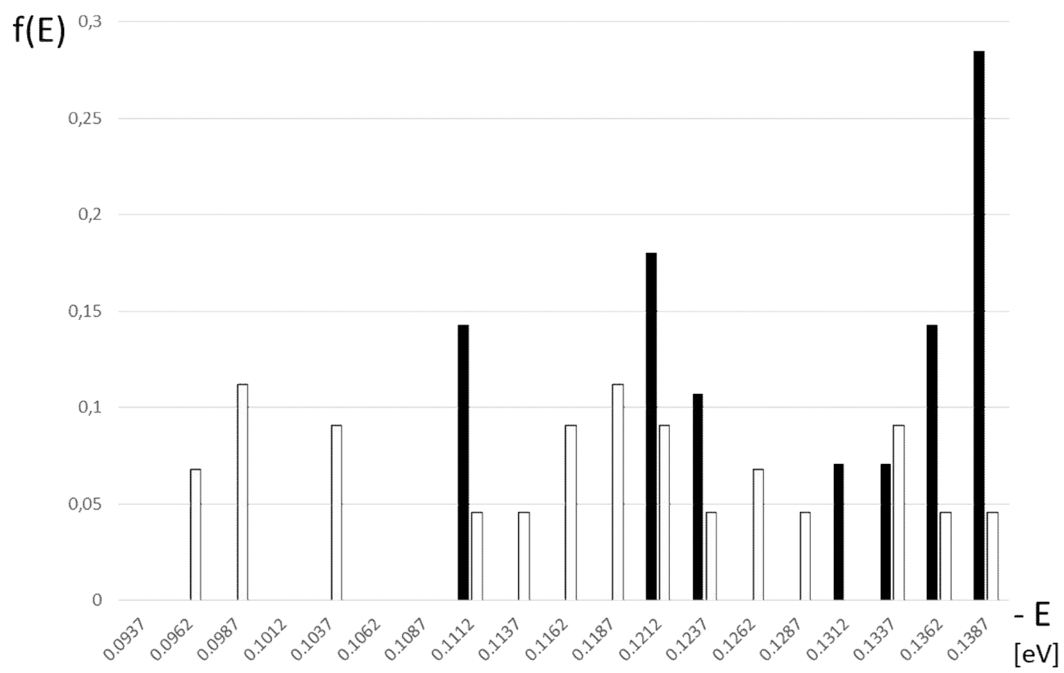

Fig.13. NES of *S. nigra* L.

Figures 3 to 13 also demonstrate that each investigated plant extract has a unique signature with respect to its non-equilibrium energy spectrum due the specific distribution of hydrogen bond energies within the solutions. So, our next step was to check the possibility of analyzing these spectra with the methods of information theory.

The Shannon entropies of the investigated plant extracts, including that of deionized water, are presented in ascending order in Table 1.

S. nigra L	Salvia divinorum Epling	.V. myrtillus L	.T. vulgaris L	Tilia cordata Mill	.S. rosmarinus Spenn	H. perforatum L	.M. longifolia L	Sideritis scardica .Griseb	.A. millefolium L	Pelargonium sidoides	**Deionized water**
2,65	2,93	2,99	3,02	3,07	3,10	3,15	3,21	3,25	3,29	3,44	3,72

Table 1. Shannon entropies (in bit units) of investigated plant extracts NES, including that of deionized water

These results clearly show that the solvent (deionized water) has the highest information entropy of the hydrogen bond energy spectrum compared to all investigated solutions. In addition, the latter display a broad range of values which could be the basis for further development of classification methods, where lower values correspond to more uniform distribution of hydrogen bonds energy among different levels, while higher values correspond to occurrence of more outstanding maxima at particular energy levels.

The values of *variation of information* calculated for the NES of each investigated solution with respect to the NES of deionized water are presented in ascending order in Table 2.

.M. longifolia L	.A. millefolium L	Salvia divinorum Epling	S. rosmarinus .Spenn	Sideritis scardica .Griseb	Tilia cordata Mill	.V. myrtillus L	.S. nigra L	.T. vulgaris L	H. perforatum L	Pelargonium sidoides
0,25	0,26	0,28	0,28	0,32	0,36	0,4	0,44	0,44	0,44	0,45

Table 2. Variation of information (in bit units) of investigated plant extracts NESwith respect to that of deionized water

The values of VI characterize the degree of overlapping between sample and reference NES spectra at commonly occurring hydrogen bonds energy levels. It should be pointed out that distinct clustering is observed around the lowest and the highest values in the calculated range.

The values of *transformational of information* calculated for the NES of each investigated solution with respect to the NES of deionized water are presented in ascending order in Table 3.

Sideritis scardica .Griseb	.T. vulgaris L	H. perforatum L	Pelargonium sidoides	.S. rosmarinus Spenn	Tilia cordata Mill	.M. longifolia L	.S. nigra L	.A. millefolium L	.V. myrtillus L	Salvia divinorum Epling
2,63	2,76	3,10	3,10	3,15	3,26	3,29	3,56	3,61	3,95	4,09

Table 3. Transformational of information (in bit units) of investigated plant extracts NESwith respect to that of deionized water

As it could be expected for general reasons, the order in Table 3 is different from those in Table 1 and 2. Transformational information actually takes into account also the shifts in non-overlapping energy levels due to alteration of hydrogen bonding.

The values of H, TI and VI for each investigated plant extract are presented in Fig. 14 as 3D coordinates, where the VI coordinate is proportional to the diameter of the corresponding point.

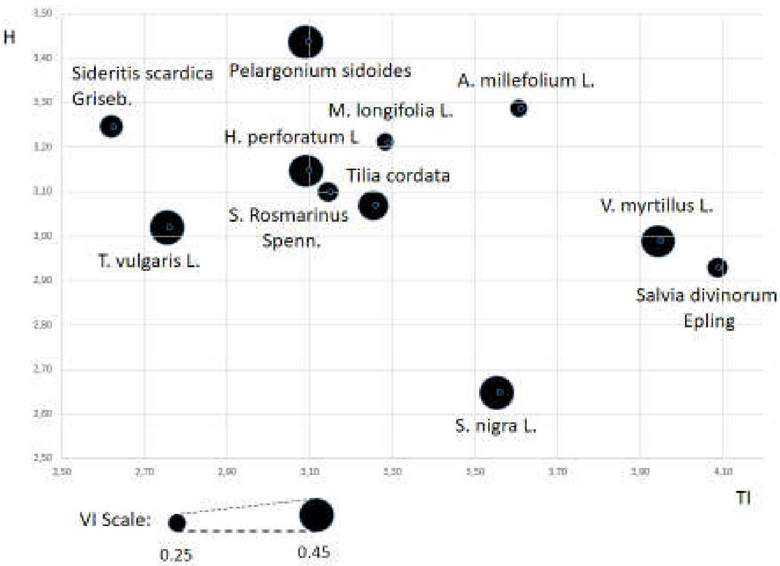

Fig. 14. H, TI and VI for each investigated plant extract

A distinct cluster is observed consisting of *Pelargonium sidoides*, *Hypericum perforatum L.*, *Tilia cordata*, *S. Rosmarinus Spenn*. and *M. longifolia L*. All of them have anti-inflammatory effect, mostly expressed in the respiratory system. In addition, *Hypericum perforatum L*. and *Tilia cordata*, being closest with respect to all three coordinates, have a common feature of fluoride content [37].The other distinct cluster consisting of *V. myrtillus L*. and *Salvia divinorum Epling* has a common feature of pronounced immunostimulatory effect [38].

In Bulgaria, medical doctors and pharmacists have been extensively applying medicinal plants and herbs. This is a national custom regulated by the Act of Health of 2005. Over the last 30 years, herbs and medicinal plants from abroad have been increasingly utilized. *S. nigra* L. fruits have been applied in cases of anti tumor therapy. [39, 40]

Conclusions

Information theoretical analysis of hydrogen bonds energies distributions in aqueous solutions of plant extracts has shown its potential for clustering according to health effects and chemical composition. Further work should be focused on extending the set of Non-equilibrium energy spectra (NES) towards much greater variety of medicinal plant species in order to explore additional possibilities for similarity patterns. In addition, the novel transformational information metric could be tested for feasibility also in other areas involving changes of probability distributions during (bio)physical and (bio)chemical processes.

Declaration

Authors have declared that no competing interests exist.

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