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APPROACH TO ASSESSING THE STATE OF PLANT BIOLOGICAL SYSTEMS BY ENTROPY

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Summary. This work reviewed the dynamics of changes in the state of walnut fruits (*Juglans regia* L.) and American pokeweed berries (*Phytolacca americana* L.) from the point of view of the thermodynamic laws of biological systems. The development of fruits/berries, accompanied by the exchange of substances and energy with the external environment, and the principles of changes in the entropy of biological systems throughout the entire life cycle are presented. An increase or decrease in the rate of change in the entropy of some system is associated with its transition to the next stage of the life cycle or the beginning of a new cycle.

Keywords: entropy, biological system**,** life cycle, energy coupling.

Introduction

Entropy (S) is not some material quantity, such as the volume or mass of any liquid, gas or solid, but an indicator of the state of the system, a mathematical function that depends on a number of variables (temperature, pressure, structure, composition, environment), which can be determined experimentally. The totality of changes in all these quantities is characterized by the entropy function. Entropy should be considered as an indicator of the state of the system, its ability for spontaneous transformations: the more the system exhausts its ability to spontaneous changes, the greater its entropy.

The state and behavior of fruits/berries and vegetables as biological systems is determined by their physiological function and structure. All structural elements of biological systems are interconnected and represent the structure of the system as a whole. Biological systems are separated by a boundary from the external environment, and at the same time retain certain connections with the environment. The hierarchical structure and function of vegetal systems are extremely diverse. In particular, the hierarchical structure and function of the walnut fruits (*Juglans regia* L.) and the berries of the American pokeweed (*Phytolacca americana* L.), in the presence of common structural elements, have a number of specific functions and have their own characteristics (Martínez et al., 2010**;** Boaghi, 2018; Ivanova et al., 2020**)**.

From the point of view of a systems approach, the structure of fruits/berries can be divided into three main levels of organization. At the first level, there is tissue structure, which characterizes the structure of the system as a whole. The second level, more detailed, is the cellular structure of the fruit/berry, which consists of plant cells. In turn, cells also consist of structural elements: cell membrane, protoplast, vacuoles, etc., which at their level are microsystems of an integral object - a cell. The third level represents the molecular structure of plant cells and consists of a huge number of different organic molecules. The plant cells of fruits/berries represent the basis of the structural composition of biological systems (Sabater, 2022). Thus, the biological system represents holarchy as a hierarchy of holons. The tissue, cellular and molecular structures in fruits/berries are holons. At

the same time, tissue structure is part of whole fruits/berries, cellular structure is part of tissue structure, and molecular structure is part of cellular structure. All structural elements of the system and each element individually are interconnected, perform certain functions and provide a high level of organization of the system (Tatarov, 2019; ISO/IEC/IEEE 15288:2023**).**

In the process of development, some structural elements of the system, after realizing their functions, lose activity and degrade, while at the same time new structural elements with new functions appear. Therefore, fruits/berries are biological dynamic systems with a hierarchical structure such as a system of systems **(**Marín et al., 2009**).** In order to determine the state of walnut fruits (*Juglans regia* L.) and American pokeweed berries (*Phytolacca americana* L.) as biological systems, the dynamics of entropy changes throughout the entire life cycle of these plants was monitorised. The rate of change in entropy is directly related to the influence of environmental parameters. However, there are some features of the change in entropy of fruits/berries in accordance with the second law of thermodynamics.

Life cycle of plant biological systems

The most general idea of changes in the entropy of fruits/berries can be traced when considering the life cycle of biological systems of plant origin, which includes two successive stages of development. At the initial stage, the formation and development of the fruit/berry on the tree/shrub, the separation of the ripened fruit/berry and the subsequent stage, germination of the embryo, growth of the tree/shrub and the beginning of fruiting occurs. In general, it is well known that the essence of the life cycle of fruits and berries predetermines by reproduction of their own kind (Ezura et al., 2023**)**.

The germination of individual fruits/berries in real conditions, without human intervention, is probabilistic in nature and is realized by single high-quality fruits under the confluence of numerous favorable external conditions (soil quality, moisture content, soil and environmental temperature, microbial activity and many other factors). In addition, in contrast to physical systems, the patterns of changes in the state of fruits/berries are to a certain extent determined and are based on biological information encoded in the genetic program of the fruit/berry, intended for the reproduction of a tree/shrub and its subsequent development and fruiting. Throughout the entire life cycle, the development of fruits/berries is largely aimed at the formation of the fetal embryo and its preservation in an active state (Martínez et al., 2010).

The life cycle can be divided into the following main periods: formation of the embryo in the fruit/berry, development and maturation of the fruit/berry, separation from the tree/shrub, germination of the embryo, growth and development of the tree/shrub.

The formation and development of the tissue, cellular and molecular structure of fruits go through a number of sequential, cyclical, irreversible states. Figure 1 shows the dynamics of the formation and growth of walnut fruit (*Juglans regia* L.) on a tree before ripening throughout its life cycle of 140 days. Final ripening of fruits occurs during the last 90. . .130 days proceed with a slight increase in mass, but with the accumulation of the necessary biologically active substances in combination with a developed enzyme system. The dynamics of their development are significantly influenced by environmental conditions, in particular, temperature, humidity, carbon dioxide and oxygen content in the air, soil moisture content, number of sunny days, etc. (Ezura et al., 2023). In pedoclimatic conditions of the Republic of Moldova the life cycle of *Phytolacca americana* growing from seeds continued from 160 to 210 days, or from March to November (Ivanova et al., 2020).

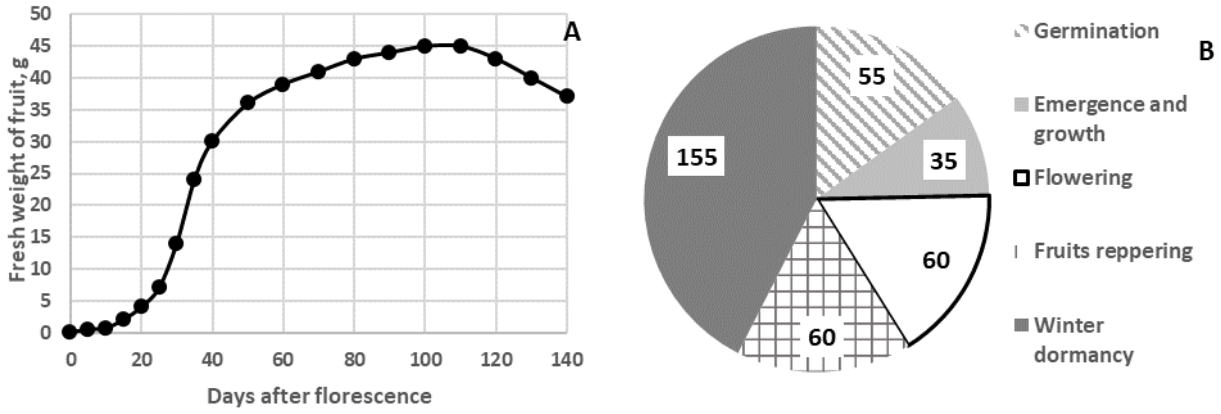


Figure 1. The life cycle of plant growth and fruit/berry formation: a) walnut (Li et al. 2012); b) American pokeweed (Ivanova et al., 2020)

Previous studies have established (Ksenzhek & Volkov, 1998) that the state of biological systems of plant origin is to a certain extent determined by the thermodynamics laws of irreversible open systems, and in particular, they are characterized by the state function of entropy. Unlike isolated physical systems, biological systems such as fruits, berries, and vegetables are living open and nonequilibrium systems. The probability of biological systems to achieve a particular state is predetermined, and in principle occurs through the formation of multicellular ordered molecular structures (Marín et al., 2009**;** Henry 2021; Sabater, 2022).

Changes in biological systems of vegetal origin are constantly accompanied by the exchange of energy and substances with the external environment. Absorption of external energy leads to the development and orderliness of the system structure, and the outflow of low-molecular substances and energy in the form of heat leads to a decrease in the entropy of the system, but increases the entropy of the external environment. Waste thermal energy does not have the potential to activate biochemical processes aimed at developing and stabilizing the structure of the system.

The change in entropy largely depends on the rate of exchange of substances and energy of biological systems with the external environment. There are often used the expressions “negative entropy” or “entropy inflow” and “entropy outflow”, which have caused widespread discussion and disapproval regarding their meanings (Jennings et al., 2005; Houck, 2014; Henry, 2021). These expressions are not entirely correct. Unlike heat and mass transfer processes, which describe the spontaneous nature of the irreversible distribution of heat and matter in space, entropy is a function of the system state; it cannot be transferred. The entropy of the system reflects the change in free energy and waste thermal energy, and depends on the exchange substances and energy with the environment (Sabater, 2022).

It is probably necessary to accentuate that, simultaneously with the specifics of the development of biological systems based on biological information, the patterns of development of fruits/berries as biological systems occur in accordance with the second law of thermodynamics according to the Boltzmann equation (Valcu, 1994; Henry, 2021**;** Sabater, 2022):

$$S = k_b \cdot \ln \Omega \qquad (1)$$

where: **S** – entropy; $\mathbf{k_b}$ – Boltzmann constant ($1.380649 \cdot 10^{-23}$ J · K^{-1}); **Ω -** possible number of system microstates

Biological systems of vegetal origin, fruits and berries, are quite complex open irreversible systems. In this regard, their state from flowering to ripening passes through a number of possible microstates and is characterized by a generalized entropy index (Sabater. 2022). In general, a change in the entropy of biological systems is functionally related to a change in entropy at each structural level of the system:

$$dS_S = dS_T + dS_C + dS_M \qquad (2)$$

where: **dSs –** changes in the entropy of the biological system as a whole; **dST –** changes in entropy of tissue structure; **dSC -** changes in entropy of cellular structure; **dSM -** changes in entropy of the molecular structure.

The change in entropy over time at each structural level of the system (**dST, dSC, dSM)** represents a complex cyclic process. The rate of entropy change at some structural levels can increase, while at other structural levels it can simultaneously decrease (Marín et al., 2009). However, in any case, at the final stage of the life cycle of fruits and berries, the rate of change in entropy always increases **dSS > 0.** Due to the fact, that when they get into the soil, they are the basis for the emergence of the life cycle of new systems, transforming into the root systems of trees and shrubs.

Energy coupling in biological systems

At the stage of the fruit/berry ripening process, the internal energy **ΔU > 0** constantly increases due to an increase in the concentration of lipids, proteins, and hydrocarbons (Fig. 2.). A constant increase in internal energy indicates that the system is transitioning from a lower to a higher energy level. The process is accompanied by a decrease in the growth of fruit/berry entropy **dSs < 0** because of the outflow of waste thermal energy into the environment (Ksenzhek & Volkov, 1998).

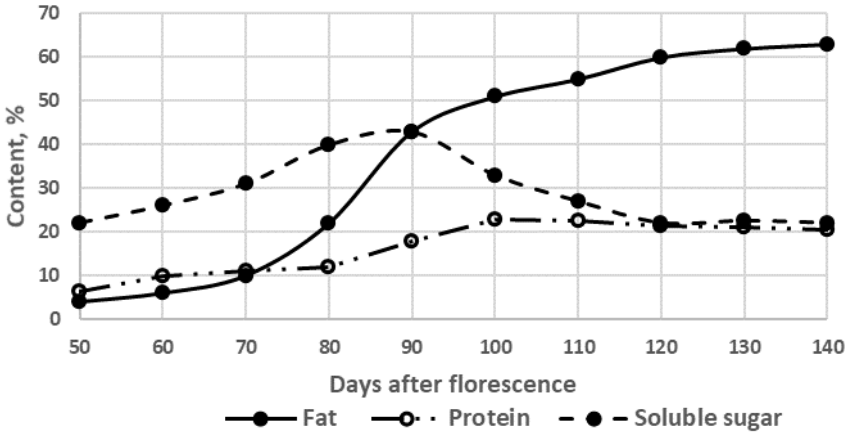


Figure 2. The changes in fat, protein and soluble sugar content (%) during the growth and ripening of walnut fruits (Li et al., 2012)

At the same time, in real conditions, when analyzing the growth and development of fruits, there is a constant increase in the internal energy of the fruit **ΔU > 0**, simultaneously with an increase in the entropy of the fruit **dSs > 0**, which is not possible from a thermodynamic point of view**.** One gets the impression that virtually no energy is spent on the processes of growth and development of the cellular structure of the fruit/berry **(ΔA = 0),** since there is a constant increase in internal energy **ΔU > 0** and a decrease in the growth of entropy of the fruit/berry **dSs < 0**.

From the point of view of classical thermodynamics, such behavior of biological systems is real because in their structure there is an internal source of energy that provides energy for those reactions that do not occur arbitrarily, but require energy expenditure. In biological systems, such a source of internal energy is exothermic biochemical reactions that release energy. At the same time, endothermic reactions occur in biological systems, which use the energy of exothermic reactions. From the point of view of thermodynamics, such reactions are energetically coupled.

Reaction coupling is realized under the condition that the free energy of possible reaction exceeds the required energy of an impossible reaction. In this case, the released free energy of real reaction is used to initiate an impossible reaction. Thus, both reactions become real and occur at the

level of the molecular structure of the fruit/berry. In particular, during the development of fruits/berries, energy coupling occurs between the reaction of ATP hydrolysis, with released free energy $\Delta\mathbf{F1}$, and the reaction of biosynthesis of molecules using part of the energy $\Delta\mathbf{F2}$. At the same time, the amount of free energy generated during ATP hydrolysis is significantly greater than the amount of energy consumed in the reactions of biosynthesis of molecular structures of fruits/berries $\Delta\mathbf{F1} > \Delta\mathbf{F2}$. Energy coupling reactions in cells are multistage and are catalyzed by a number of enzyme systems.

Therefore, in biological systems, and in particular in fruits/berries, energy coupling reactions occur, which lead to an increase in the free energy of the system $\Delta\mathbf{F1} - \Delta\mathbf{F2} = \Delta\mathbf{F} > \mathbf{0}$. At the same time, the rate of increase in the entropy of fruits/berries decreases ($\mathbf{dSs} < \mathbf{0}$) as a consequence the fact that the fruits release molecules of H_2O, O_2, CO_2 into the external environment, dissipating waste thermal energy.

At the final stage of the life cycle, ripened fruits and berries pass into a stationary state in which the free energy of the system decreases $\Delta\mathbf{F} \rightarrow \mathbf{0}$, and the rate of entropy change increases $\mathbf{dS_S} > \mathbf{0}$. One of the possible ways to further develop the life cycle of ripened fruits and berries is their transition to the food system.

Conclusions

The fruits of walnut (*Juglans regia* L.), the berries of American pokeweed (*Phytolacca americana* L.) and many other plants are open, nonequilibrium biological systems with a hierarchical structure of type as the system of systems. The laws of thermodynamics of irreversible open systems determine their development, and in particular, they are characterized by the state function of entropy. At certain stages of the life cycle, the formation of the fruit/berry structure is to a certain extent predetermined and obeys the biological laws of development. The process of growth and development of fruits and berries is accompanied by a constant periodic cyclical nature of exchanges in substances and energy with the external environment. Under certain conditions, the entropy of biological systems reaches relative stability during the transition to a new life cycle of development. A significant increase or decrease in entropy modification indicates the completion of this life cycle of fruit and berry development. Their subsequent development is associated with the process of reproduction, the beginning of a new life cycle, or the use of walnut fruits and American pokeweed berries as food or a substrate for microorganisms. In this case, these fruits become food systems.

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References

1. Boaghi E. Modificările biochimice şi tehnologice ale nucilor pe parcursul prelucrării şi păstrării. Teza de doctor în tehnică. Chisinau: UTM, 2018, 153p.
2. Ezura K., Nomura Y., Ariizumi T. Molecular, hormonal, and metabolic mechanisms of fruit set, the ovary-to-fruit transition, in horticultural crops. In: *J. Exp Bot.* 2023, 2: erad214. https://doi.org/10.1093/jxb/erad214.
3. Henry M.. Thermodynamics of life. In. *Substantia,* 2021, 5(1): 43-71. https://doi.org/10.36253/Substantia-959.
4. Houck P.D. Should negative entropy be included in the fundamental laws of biology? OA *Biology*. 2014, 2(1): 7. https://www.researchgate.net/publication/271645203_Should_negative_ entropy_be_included_in_ the_fundamental_laws_of_biology.
5. ISO/IEC/IEEE 15288. System life cycle processes. 2023, 116 p. https://www.iso.org/standard/81702.html.

6. Ivanova R., Simkova J., Brindza J. Growth particularities of American pokeweed – plant with multipurpose utilization. Int. J. AGROFOR, 2020, 5 (Issue 3): 5-12. https://doi.org/10.7251/AGRENG2003005I
7. Jennings R.C., Engelmann E., Garlaschi F., Casazza A.P., Zucchelli G. Photosynthesis and negative entropy production. In: *Biochim. Biophys. Acta*, 2005, 1709: 251–255. https://doi.org/10.1016/j.bbabio.2006.05.017.
8. Ksenzhek, O.S., Volkov A.G. Plant Energetics. Academic Press, 1998, 389 p. https://library.wur.nl/WebQuery/titel/940199.
9. Li Y., Ma S., Wang Y., Xuan X., Hou H, Sun Q., Yang K. The dynamics of fat, protein and sugar metabolism during walnut *(Juglans regia* L.) fruit development. In: *African J. Biotech.* 2012. 11(5): 1267-1276. https://doi.org/10.5897/AJB11.2852.
10. Marín D., Martín M., Sabater B. Entropy decreases associated to solute compartmentalization in the cell. In: *BioSystems*, 2009, 98: 31–36. https://doi.org/10.1016/j.biosystems.2009.07.001.
11. Sabater B. Entropy perspectives of molecular and evolutionary biology. In: *Int. J. Mol. Sci.* 2022, 23, 4098. https://doi.org/10.3390/ijms23084098.
12. Sandler S. I. Chemical, biochemical and engineering thermodynamics (Fifth ed.). Publisher: John Wiley & Sons, Inc., Hoboken, New York. 2020. https://www.worldcat.org/title/1197750870.
13. Tatarov P. Principii conceptuale ale calității alimentelor și capabilității proceselor tehnologice. Manual. Chisinau: Tehnica - UTM, 2019, 160 p. http://repository.utm.md/ bitstream/handle/5014/15215/Principii_CalitateaAlimentelor_Manual_DS.pdf?sequence=1
14. Valcu R. Termodinamică chimică**.** București: Ed. Tehnica, 1994, pp. 185–208.