Methods for determining exergy photosynthesis in crop production

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Abstract. It is shown that there is an energy types group that does not contain irreversible energy - anergies, and completely or partially consist of a transformable part - exergy. In the crop production productivity bioenergetic theory, as a similar value, one can take the light radiation exergy - that light radiation energy part supplied to plants that can potentially be used by them for photosynthesis and converted into a crop product. As a methodological basis for determining the complex light exergy, as well as any other spectral composition light emission, concerning plant photosynthesis arriving over the given period, it is taken the radiation density distribution over the radiation source spectrum, taking into account the photosynthesis spectral efficiency (action spectrum). The determination method is shown step by step using the two light radiation sources assessing the photosynthetic exergy example - a warm-cold LED lamp LL LEDs and a LED Phyto-lamp LED - M80. As a result, the photosynthetic exergy values were obtained, respectively - 1552.6 and 1728.5 J. The developed computer program, which is based on the light radiation exergy magnitude, is designed to calculate optimization indicators and select, on their basis, the plants' type (variety, hybrid) to obtain the required products for compliance with the land ecological conditions. The program use should ensure a reduction in the crop production cost by 30-40%, energy consumption by 25-30% and increase the land-use efficiency by 30-35%.

1. Introduction
Almost all natural man-made or non-man-made processes use energy' various types and categories. Despite their generality, reflected by the energy conservation law, formulated in the thermodynamics first law, energy different types and categories have a different ability to convert into energy other types. This ability allows quantifying the energy' any kind potential convertibility to any other kind. First, it is advisable to single out an energy types group, which is complete, without a trace, converted into energy' any other types. They do not contain irrecoverable energy, which we will call energy, and completely or partially consist of a transformable part called exergy (from the Greek ek, ex - a prefix meaning a high degree, and ergon - work).

Another group' energy types, on the contrary, cannot be completely transformed into energy' other types. They contain an energy irreversible part - anergy. The article will discuss the exergy quantitative determination [1, 2, 3].

An important principle of any knowledge branch theoretical foundations that has its values is the ability to determine this industry-main value, as well as to determine this value maximum (theoretical) value. In the crop production productivity bioenergetic theory, as a similar value, one can take the light
radiation (LR) exergy - that LR energy part supplied to plants that can potentially be used by them for photosynthesis and converted into a crop product.

This initial value makes it possible to correctly determine the crop production and agroecology two main values: a given species (variety, hybrid) potential productivity under given environmental conditions and its growing environment potential fertility (for a closed artificial agroecosystem (CAES) conditions, this is a substrate space), with certain ecological (climatic, nutritional) conditions of a plant’s given species (variety, hybrid).

Also, due to the need for such energy categories transformations joint exergetic analysis as:

- technogenic energy in agricultural technologies;
- natural energy bioconversion by organisms into the plants' productivity (yield);
- the growing environment fertility,

it is advisable to evaluate and express the processes in the same exergy units. In the same units, it is convenient to express other agroecological quantities: the growing environment agrobioclimatic and reclamation potentials, the plants' potential productivity in the existing environmental conditions.

2. Methods

As a methodological basis for determining the total solar radiation, as well as any other spectral composition light emission (E_m), concerning plant photosynthesis arriving over the period \( t_1 - t_2 \), taken the radiation density distribution over the radiation source spectrum \( (\varphi(\lambda)) [mW/m^2] \) (figures 1 and 2), taking into account the photosynthesis spectral efficiency (action spectrum) \( (K(\lambda)) \), by the formula:

\[
E = 0.95 \int_{t_1}^{t_2} \int_{\lambda=300}^{\lambda=750} \varphi(\lambda) K(\lambda_f) d\lambda d\lambda_f [W/m^2],
\]

where \( \lambda \) is the wavelength in the action spectrum, 0.95 is the monochromatic radiation exergy value with a wavelength of 680 nm concerning plant photosynthesis at a three minimum quantum consumption [4].

The photosynthesis spectral efficiency \( K(\lambda) \) is a factor that corrects for the radiation density distribution measured value over the light source spectrum, which makes it possible to evaluate the radiation efficiency on the photosynthesis chemical reaction. In other words, it shows how much of the study is involved in the photosynthesis process. The photosynthesis spectral efficiency \( K(\lambda) \) was obtained by experimental data statistical processing on the different plant species photosynthesis spectral efficiency experimental determination by various authors at irradiation non-saturating values and is expressed in relative units (table 1). The values are reflected in the Electrical Engineering USSR Ministry industry standards and the USSR Ministry of Agriculture [5].

| Start step wavelength \( \lambda, \text{nm} \) | \( K(\lambda), \% \) | \( \lambda, \text{nm} \) | \( K(\lambda), \% \) | \( \lambda, \text{nm} \) | \( K(\lambda), \% \) | \( \lambda, \text{nm} \) | \( K(\lambda), \% \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 300             | 420             | 56.7            | 540             | 35              | 660             | 95.8            |
| 310             | 430             | 57.8            | 550             | 34.8            | 670             | 97.5            |
| 320             | 440             | 57.4            | 560             | 34.2            | 680             | 100             |
| 330             | 450             | 48.8            | 570             | 38.1            | 690             | 67.6            |
| 340             | 460             | 48.8            | 580             | 50.4            | 700             | 25.1            |
| 350             | 470             | 45              | 590             | 57              | 710             | 12.5            |
| 360             | 480             | 40.5            | 600             | 56.8            | 720             | 7.4             |
| 370             | 490             | 37.3            | 610             | 55.2            | 730             | 4.9             |
We will show the determination technique step by step using the two radiation sources assessing the photosynthetic exergy example (figures 1 and 2), entering each stage results in table 2.

| Wavelength (nm) | Photosynthesis effectiveness (%) | Warm-cold (mix) LED downlight $\phi (\lambda)_a$, mW/m² | $K (\lambda)_a \cdot \phi (\lambda)_a$, mW/m² | LED Phyto-lamp $\phi (\lambda)_a$, mW/m² | $K (\lambda)_a \cdot \phi (\lambda)_a$, mW/m² |
|-----------------|---------------------------------|-----------------------------------------------------|-----------------------------------------------|---------------------------------|-----------------------------------------------|
| 380             | 52.8                            | 713.51                                              | 376.73                                        | 721.19                          | 380.79                                        |
| 390             | 54                              | 775.51                                              | 418.77                                        | 787.87                          | 425.45                                        |
| 400             | 55.2                            | 834.71                                              | 460.76                                        | 812.45                          | 448.47                                        |
| 410             | 56                              | 905.02                                              | 506.81                                        | 821.33                          | 459.94                                        |
| 420             | 56.7                            | 997.25                                              | 565.44                                        | 823.26                          | 466.79                                        |
| 430             | 57.8                            | 1102.98                                             | 637.52                                        | 821.64                          | 474.91                                        |
| 440             | 57.4                            | 1187.05                                             | 681.36                                        | 808.39                          | 464.01                                        |
| 450             | 48.8                            | 1218.77                                             | 594.76                                        | 750.18                          | 366.09                                        |
| 460             | 48.8                            | 1192.29                                             | 581.84                                        | 557.02                          | 271.83                                        |
| 470             | 45                              | 1199.94                                             | 539.97                                        | 279.07                          | 215.58                                        |
| 480             | 40.5                            | 1287.27                                             | 521.34                                        | 121.48                          | 49.20                                         |
| 490             | 37.3                            | 1416.64                                             | 528.41                                        | 52.88                           | 19.73                                         |

**Figure 1.** Spectrum of a warm-cold LED luminaire LL LED.

**Figure 2.** Spectrum of LED Phyto-luminaire LED - M80.

**Table 2.** The optical radiation density determination transmitted to the plant, taking into account the photosynthesis relative spectral efficiency coefficients.
Due to the analytical expressions' absence for the integrands, we determine the integral value (1) graphically, using the data in table 1 and the spectrometer in figures 1 and 2, replacing the integral with the sum sign:

\[ E_{\text{lerd}} = \sum_{\lambda_1}^{\lambda_2} \varphi(\lambda) \Delta \lambda K(\lambda) f \Delta \lambda \left[ \frac{Vt}{m^2} \right], \]  

(2)

where \( E_{\text{lerd}} \) is the light emission radiation density; \( \lambda_1 = 300 \text{ nm}, \lambda_2 = 750 \text{ nm} \).

1. Using the UPRTek spectrometer, we measure the light sources' emission density distribution value for each wavelength interval (table 2, columns 1, 3 and 5). The interval size is selected based on table 1.

2. For each wavelength interval, we determine the radiation fraction involved in photosynthesis, for which we multiply the columns 3 and 5 values by the coefficient from column 2, dividing it by one hundred.

3. The data obtained can be used to determine the LR exergy obtained by the plant, taking into account its leaves area and the illumination duration by the formula:

\[ E_{\text{em}} = t \cdot S \cdot E_{\text{lerd}} \left[ \frac{J}{m^2} \right], \]  

(3)

where \( t \) is the daylight hours duration (sec). For the calculation, the daylight hours duration is taken equal to 12 hours (43,200 seconds). Taking into account that the illumination is created artificially in
the CAAES, its radiation density does not change during daylight hours. Let us take the same condition for comparison for sunlight; $S$ - plant leaf area. For the cucumber plant under study, the leaf area is 2096 mm$^2$; $K(\lambda)$ - coefficient of the relative spectral efficiency of photosynthesis under the tabular values.

3. Results and discussion
For example, for cucumber with a leaf area $S=2096\text{mm}^2$ and a lighting duration of 12 hours/day ($t = 43200$ sec/day):

$$E_{em} = t\ S\ E_n = 43200\ (sec)\ 2.096\ 10^{-6}(m^2)\ E_{led\ (W/m^2\ sec}).$$

We will summarize the data in table 3.

| Warm-cold LED luminaire | LED Phyto-lamp |
|------------------------|---------------|
| $E_{of\ J}$            | 1552.6        |
|                        | 1728.5        |

So, we have quantitatively determined the crop industry-main value - the light radiation exergy - that LR energy part supplied to plants that can potentially be used by them for photosynthesis and converted into a crop product.

4. Conclusions
The initial value has been determined, which makes it possible to carry out a natural energy transformations (bioconversion) joint exergy analysis by organisms into the plants' productivity (yield). The analysis is carried out according to the method described in the patent [6], according to the computer program [7].

The computer program is designed to calculate optimization indicators and select, on their basis, the plants' type (variety, hybrid) to obtain the required products for compliance with the land ecological conditions, taking into account the varietal zonal agricultural technology and its implementation means [8, 9, 10].

These indicators are based on the exergy magnitude LR $E_{em} (\Delta e_i)$. The program algorithm is given in the sources [6,7]. This methodology and program is the agricultural technology theorization beginning for harvesting and is used in a textbook for universities on agricultural biotechnology [11].

The program application area is the agro-industrial complex crop production, both as consulting services part and directly in the individual producers planning services.

The program use should ensure a reduction in the crop production cost by 30-40%, energy consumption by 25-30%. To increase the land-use efficiency by 30-35%.

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