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Resources and potential for utilization of low-exergy heat from mung bean sprouts cultivation – case study

PAWEŁ MIREK[a*]
MARCIN PANOWSKI[a]
KLAUDIA SŁOMCZYŃSKA[a, b]
MICHAŁ STANEK[c]
TOMASZ BĄKOWSKI[c]

[a] Czestochowa University of Technology, Faculty of Infrastructure and Environment, Dąbrowskiego 69, 42-201 Częstochowa, Poland

[b] ENERGOPROJEKT-KATOWICE SA, Jesionowa 15, 40-159 Katowice, Poland

[c] Uniflora Sp. z o.o., Lwowska 8, 42-202 Częstochowa, Poland

Abstract Poland is a significant producer of vegetable sprouts, which, due to the high content of nutrients, are produced for food purposes. The cultivation cycle of these plants, especially the mung beans (Vigna radiata), is associated with significant exploitation of natural resources (as much as 275 dm^3 of water per 1 kg of dry seeds) and requires appropriate temperature conditions. However, since producing of vegetable sprouts is an exothermic process, there are reasons to organize the growth conditions of these plants in a quasi-autonomous manner. Estimated preliminary studies show that during the entire period of sprout growth, as much as 2.86 MJ of heat from 1 kg of dry seeds can be used, which, taking into account the scale of production of these plants, places them among the significant sources of low-temperature waste heat. The paper presents the results of temperature measurements carried out in a growth chamber used for the industrial production of the mung bean vegetable sprouts. Based on the prepared energy balance, the total amount of heat generated (4.9 GJ) and recovered (3.3 GJ) in the seed germination process was determined. The amount of energy lost

*Corresponding Author. Email: pawel.mirek@pcz.pl

in the process of imbibition and the amount of heat needed to ensure optimal plant growth conditions were determined. The study shows that the use of low-temperature heat generated by plants allows for a significant reduction in the energy consumption of the production process.

Keywords: Mung beans; Waste heat recovery; Energy balance; Biomass; Sprouts production

Nomenclature

A	–	cross-section, m^2
A_c	–	heat exchange surface area, m^2
A_F	–	front wall area, m^2
c	–	specific heat, J/(kgK)
d	–	wall partition thickness, m
$E_{a_{\mathrm{con}}}$	–	energy transferred in the gas phase by convective mixing, J
$E_d,\ E_{ds}$	–	energy contained in the imbibition and irrigation water, respectively, which is discharged through a leak to the drain collector, J
E_{imb}	–	energy supplied to the growth chamber during the imbibition phase, J
$E_{\mathrm{in}},\ E_{\mathrm{out}}$	–	energy supplied to and removed from the system, J
$E_{\mathrm{mass,in}},\ E_{\mathrm{mass,out}}$	–	energy transport with mass into and out of the system, respectively, J
E_s	–	energy contained in the water flowing through the plant mass in the irrigation process, J
g	–	gravitational acceleration, m/s^2
h	–	specific enthalpy, J/kg
$h_{a_{\mathrm{in}}}$	–	enthalpy of air supplied to the growth chamber, J/kg
$h_{a_{\mathrm{out1}}},\ h_{a_{\mathrm{out2}}}$	–	enthalpy of air removed from the growth chamber through pipeline 1 and 2, respectively, J/kg
$h_{\mathrm{imb_{in}}}$	–	enthalpy of water supplied to the growth chamber during the imbibition process, J/kg
$h_{\mathrm{imb_{out1}}},\ h_{\mathrm{imb_{out2}}}$	–	enthalpy of water discharged from the growth chamber after the imbibition process directly into the drain channel and through the growth cabin, respectively, J/kg
$h_{\mathrm{imb_{vap}}},\ h_{w_{\mathrm{vap}}}$	–	enthalpy of water evaporated during the imbibition and irrigation phase, respectively, J/kg
$h_{\mathrm{in}},\ h_{\mathrm{out}}$	–	enthalpy of fluid entering and leaving the control volume, respectively, J/kg
$h_{w_{\mathrm{in}}}$	–	enthalpy of water supplied to the growth chamber during the irrigation phase, J/kg
$h_{w_{\mathrm{out1}}},\ h_{w_{\mathrm{out2}}}$	–	enthalpy of water discharged from the growth chamber during the irrigation process directly into the outlet channel and through the growth cabin, respectively, J/kg
m	–	mass, kg
$\dot{m}_{a_{\mathrm{in}}},\ m_{a_{\mathrm{in}}}$	–	mass flow rate and mass, respectively, of air supplied to the growth chamber, kg/s, kg

$\dot{m}_{a_{\text{out1}}},\ m_{a_{\text{out1}}}$	–	mass flow rate and mass, respectively, of air removed from the growth chamber through pipeline 1, kg/s, kg
$\dot{m}_{a_{\text{out2}}}, m_{a_{\text{out2}}}$	–	mass flow rate and mass, respectively, of air removed from the growth chamber through pipeline 2, kg/s, kg
m_{CV}	–	amount of mass accumulated in the control volume, kg
$\dot{m}_{\text{imb}_{\text{acc}}},\ m_{\text{imb}_{\text{acc}}}$	–	mass flow rate and mass, respectively, of water accumulated in seeds during the imbibition process, kg/s, kg
$\dot{m}_{\text{imb}_{\text{in}}},\ m_{\text{imb}_{\text{in}}}$	–	mass flow rate and mass, respectively, of water supplied to the growth chamber during the imbibition process, kg/s, kg
$\dot{m}_{\text{imb}_{\text{out}}},\ m_{\text{imb}_{\text{out}}}$	–	mass flow rate and mass, respectively, of water discharged from the growth chamber after the imbibition process, kg/s, kg
$\dot{m}_{\text{imb}_{\text{out1}}},\ m_{\text{imb}_{\text{out1}}}$	–	mass flow rate and mass, respectively, of water discharged from the growth chamber during the imbibition process directly into the drain channel, kg/s, kg
$\dot{m}_{\text{imb}_{\text{out2}}},\ m_{\text{imb}_{\text{out2}}}$	–	mass flow rate and mass, respectively, of water discharged from the growth chamber during the imbibition process through the growth cabin, kg/s, kg
$\dot{m}_{\text{imb}_{\text{vap}}},\ m_{\text{imb}_{\text{vap}}}$	–	mass flow rate and mass, respectively, of water evaporated during the imbibition phase, kg/s, kg
$\dot{m}_{\text{in}},\ m_{\text{in}}$	–	mass flow rate and mass, respectively, of fluid entering the control volume, kg/s, kg
$\dot{m}_{\text{out}},\ m_{\text{out}}$	–	mass flow rate and mass, respectively, leaving the control volume, kg/s, kg
$\dot{m}_{w_{\text{acc}}},\ m_{w_{\text{acc}}}$	–	mass flow rate and mass, respectively, of water accumulated in seeds during the irrigation phase, kg/s, kg
$\dot{m}_{w_{\text{in}}},\ m_{w_{\text{in}}}$	–	mass flow rate and mass, respectively, of water supplied to the growth chamber during the irrigation phase, kg/s, kg
$\dot{m}_{w_{\text{out}}},\ m_{w_{\text{out}}}$	–	mass flow rate and mass, respectively, of water discharged from the growth chamber during the irrigation phase, kg/s, kg
$\dot{m}_{w_{\text{out1}}},\ m_{w_{\text{out1}}}$	–	mass flow rate and mass, respectively, of water discharged from the growth chamber during the irrigation process directly into the outlet channel, kg/s, kg
$\dot{m}_{w_{\text{out2}}},\ m_{w_{\text{out2}}}$	–	mass flow rate and mass, respectively, of water discharged from the growth chamber during the irrigation process through the growth cabin, kg/s, kg
$\dot{m}_{w_{\text{vap}}},\ m_{w_{\text{vap}}}$	–	mass flow rate and mass, respectively, of water evaporated during the irrigation phase, kg/s, kg
$m_1,\ m_2$	–	amount of mass in the control volume at the time t_1, and t_2, respectively, kg
Q	–	heat, J
Q_c	–	heat coming from the heat storage through the heat transmission, J
$Q_{\text{in}},\ Q_{\text{out}}$	–	heat entering and leaving the control volume, respectively, J
Q_{vap}	–	heat needed to evaporate the moisture, J
Q_{wall}	–	heat exchanged in the gas phase by heat transmission through the front wall of the chamber, J
V_a	–	volume of fresh air supplied to the growth chamber, m^3
v	–	fluid velocity, m/s

$V_d,\ V_s$	–	volume of water supplied directly to the drain collector and through the growth cabin, respectively, m^3
V_{imb}	–	volume of water supplied to the growth cabin during imbibition, m^3
t	–	time, s
T_a	–	inlet air temperature, K
T_{ex}	–	outside air temperature on the front door side, K
T_{imb}	–	temperature of the water for soaking the seeds during imbibition, K
T_{in}	–	average internal temperature in the growth chamber, K
$T_{\mathrm{in1}},\ T_{\mathrm{in2}}$	–	outlet air temperature in pipeline 1 and 2, respectively, K
T_{out}	–	used water temperature measured at the drain, K
T_p	–	temperature of used water discharged directly from the growth cabin, K
T_{ref}	–	reference air temperature in the growth chamber, K
T_w	–	irrigation water temperature, K
$T_{0.8},\ T_{1.1},\ T_{1.4}$	–	temperature of sprouts in the cabin at height 0.8 m, 1.1 m, and 1.4 m, respectively, K
$W_{\mathrm{in}},\ W_{\mathrm{out}}$	–	work transfer into and out of the system, J
z	–	leveling height, m

Greek symbols

$\alpha_{\mathrm{ex\_}v},\ \alpha_{\mathrm{in\_}v}$	–	external and internal convective heat-transfer coefficient for vertical heat transport, respectively, $W/(m^2K)$
$\alpha_{\mathrm{ex\_}h},\ \alpha_{\mathrm{in\_}h}$	–	external and internal convective heat-transfer coefficient for horizontal heat transport, respectively, $W/(m^2K)$
λ	–	thermal conductivity coefficient, W/(m K)
μ	–	molecular weight, kg
ρ	–	density, kg/m^3
ΔE_{CV}	–	change in energy in the control volume due to the change in internal, kinetic and potential energy, J
ΔH_{vap}	–	enthalpy of water evaporation, kJ/mol
ΔQ	–	heat change in the control volume, J

Subscripts

a	–	air
w	–	water

Abbreviations

ADP	–	adenosine diphosphate
ATP	–	adenosine triphosphate
Pi	–	inorganic phosphate
WHR	–	waste heat recovery

1 Introduction

The European Green Deal clearly identifies achieving zero net greenhouse gas emissions by 2050 as the main task of the European Union's energy policy. This assumption introduces the necessity of economy decarbonization, among others through increasing the share of renewable energy sources (RES) in heat and electricity production technologies, increasing energy efficiency of buildings, wider use of hydrogen technologies and nuclear energy, as well as reduction of energy consumption. The latter goal can be achieved by reusing waste energy. Waste heat accompanies practically all production processes and is often treated as a by-product that is discharged into the environment and irretrievably lost [1,2]. Its reuse (called waste heat recovery – WHR) allows reducing the consumption of conventional fuels, which directly results in a significant reduction in greenhouse gas emissions. The importance of WHR for rational energy policy is emphasized by the huge waste heat resources present in the world. According to the simulations carried out by Firth *et al.* [3] by 2030 they will be at the level of 23% to 53% of global primary energy consumption (depending on the energy scenario adopted for the calculations). Taking into account that about 25% of the total energy consumption falls on the industrial sector [4], it is worth paying attention to the possibility of using waste heat in this very area. In particular, the recovery of heat with low quality parameters, which in production processes constitutes up to 40% of total waste energy, seems to be an important issue [5].

Taking into account the quality parameters, in particular the temperature of the energy carrier, three types of waste heat can be distinguished [6]:

- low-temperature (below 503 K),
- medium-temperature (503–923 K),
- high-temperature (above 923 K).

Despite the widespread use of low-temperature waste heat sources in the industry, its reuse is troublesome and often requires high financial outlays. The difficulties are mainly related to the low-quality parameters of heat carriers, which may be insufficient to directly meet the needs of consumers [7]. Another problem may be the lack of a low exergy heat collection installation. Ensuring effective heat exchange between factors of similar temperature requires reducing their flow velocity. This may result in the necessity of using very large heat exchangers, which increases investment expenditure and is sometimes impossible to implement [8]. The solution may be the design of hybrid systems using, among others, heat pumps [9,10], cryogenic energy stores [11,12], or the organic Rankine cycle (ORC) [13,14]. Another type of difficulty in utilizing waste heat is the large degree of dispersion in different parts of the production process. Combining the media from all heat sources with similar temperatures into a single stream can help in efficient energy recovery, but often leads to a reduction in the amount of energy recovered compared to recovering directly from each source. On the other hand, such action significantly reduces the cost of the waste heat recovery installation and may be more economically attractive for the company [8].

Despite the many difficulties with low-temperature heat recovery, there are many manufacturing processes where it is implemented. Table 1 shows examples of WHR installations in various industry sectors.

Table 1: Examples of the use of WHR in the manufacturing processes of various industries.

Industry sector	Waste heat source	Working medium temperature (K)	Nominal heat output	Ref.
Food industry	Brewing process – microbrewery (Mexico)	315–353	No data available	[15]
	Dairy waste water – Arla (Denmark)	295–298	1.5 MW	[16]
Petrochemical industry	Catalytic reforming plant – Shijiazhuang Refining & Chemical Company (China)	371–488	3.3 MW	[17]
Metallurgical industry	Wastewater from steel production – Angang Lingshan (China)	303–313	9.5 MW	[18]
	Ferrosilicon production – Elkem Rana (Norway)	393	22 MW	[19]
Textile industry	Yarn Dyeing Process – Dyeing Plant (China)	353–368	No data available	[20]
	Exhaust fumes – garment factory (Bangladesh)	459–482	3586 MWh/annually	[21]
	Textile drying process – Textile factory (Turkey)	393–453	No data available	[22]
Paper industry	Paper drying process – Skjern Papirfabrik (Denmark)	316	No data available	[23]

One of the examples of sources of low-quality waste energy are biological processes occurring during the production of vegetable sprouts for food purposes. The exothermic nature of these processes accompanies both the germination phase and the further growth of plants, resulting in the formation of a significant stream of low-temperature heat (293–313 K), usually discharged to the environment. The mung bean is one of the most popular plant species produced for food purposes in the form of sprouts. It is a legume plant whose sprouts are grown in the dark, in a hot and humid environment, and is a valuable source of protein and essential amino acids [24]. Bean germination begins inside the seed, causing the embryo to revive and grow. The beginning of germination is the period of water absorption by the plant and the end is the appearance of the embryonic root (i.e. sprout). After the appearance of the root, the growth of the seedling begins [25]. Sprouts produced in the production process for food purposes are defined as 'the product obtained by the germination of seeds and their development in water or another medium, harvested before the development of proper leaves and intended to be eaten whole, including the seed' [26]. A sprouted seed, therefore, includes the sprout, seedling, and shoots [27]. Thus, the production of sprouts for food purposes includes not only the germination process but also the growth of the seedling until the appearance of the first leaves. Figure 1 shows the main phases of the mung bean seed germination.

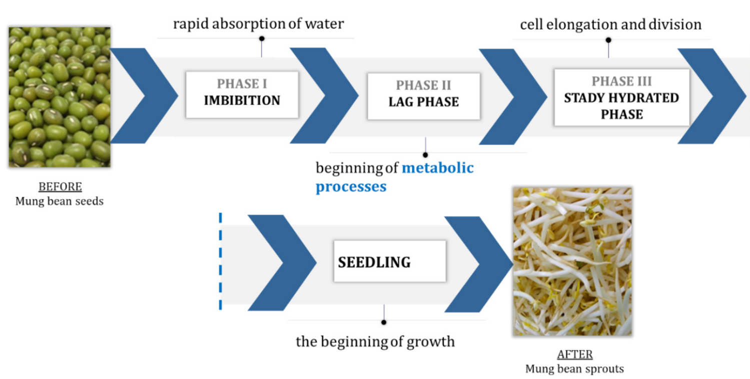

Figure 1: Main stages of the mung bean seed germination process.

Waste heat in the germination process is generated according to two mechanisms [28]. The first one is related to the swelling of seeds, which intensively absorb water in the first stage of germination, called the imbibition stage [29]. The source of heat is then the physicochemical processes related to mechanical stresses that occur in the seed coat. After the rupture of the seed coat and initiation of metabolic processes, particularly cellular respiration, the main role in heat generation begins to be played by catabolic reactions defined by the equation [28,30]:

$$\text{organic substrate} + O_2 + x\,\text{ADP} + x\,\text{Pi} \rightarrow CO_2 + H_2O + x\,\text{ATP} + Q \quad (1)$$

and anabolic reactions, according to the following equation:

$$\text{organic substrate} + y\,\text{ATP} \rightarrow \text{growth} + y\,\text{ADP} + y\,\text{Pi} + Q. \quad (2)$$

where x and y are stoichiometric coefficients.

During catabolic processes, the spare substances (mainly carbohydrates) found in seeds are oxidized to carbon dioxide and water [25]. The adenosine-5′-triphosphate (ATP) molecule is also produced, which stores and transports the energy obtained from the decomposition of organic matter stored in the spare tissue in seeds. This energy is involved in anabolic reactions, where it is used to create new cells. During these reactions, energy in the form of heat is dissipated to the environment [30,31]. This heat is a by-product of the cellular respiration process occurring in the seeds [28] and can be reused in the sprout production process. This is extremely important since the cultivation cycle of these plants involves the use of significant amounts of water and requires appropriate temperature conditions. The use of waste heat can help to increase the efficiency of the process and thus reduce the use of conventional energy sources.

Although the mechanism of heat generation by plants is known and research on the determination of heat flux of germinating plants was initiated by Pierce already in 1908 [32], there is still a lack of literature reports on the possibility of its practical application and information on the amount of heat generated by seeds during the production of vegetable sprouts. So far, the energy released by seeds of soybean [33], wheat [31], corn [34] or quinoa [35,36], among others, has been studied under laboratory conditions. These studies were biological analyses and focused only on attempts to determine the course of the germination phase and the influence of various environmental factors on their germination rates [30,31]. Since the object of interest was mainly the germination process itself without seedling growth, the main experiments lasted no longer than 72 hours. From the point of view of the analysis of energy processes occurring under conditions of industrial sprout cultivation, this period is too short. This is because the sprouts' cultivation includes not only the germination process but also the growth phase (up to the appearance of the first proper leaves) and lasts several days, depending on the plant species cultivated. For this reason, an energy analysis of the growth process must be carried out over the entire production period, from the imbibition phase to the fully formed sprout phase.

The paper presents the results of experimental studies of the growth chamber of the mung bean. Based on temperature measurements carried out during the whole period of the plant growth, the amounts of heat supplied to and removed from the growth chamber were evaluated. The obtained results allowed to determine the amount of energy possible to be reused and the amount of heat generated by the plant mass.

2 Mass and energy balance of the growth chamber

Figure 2 shows a block diagram of the installation for the production of the mung bean vegetable sprouts, with the growth chamber being the subject of the analysis. The main component of the installation is the growth chamber, in which the process of plant cultivation is carried out. Providing appropriate conditions for the growth of plants is possible by periodically

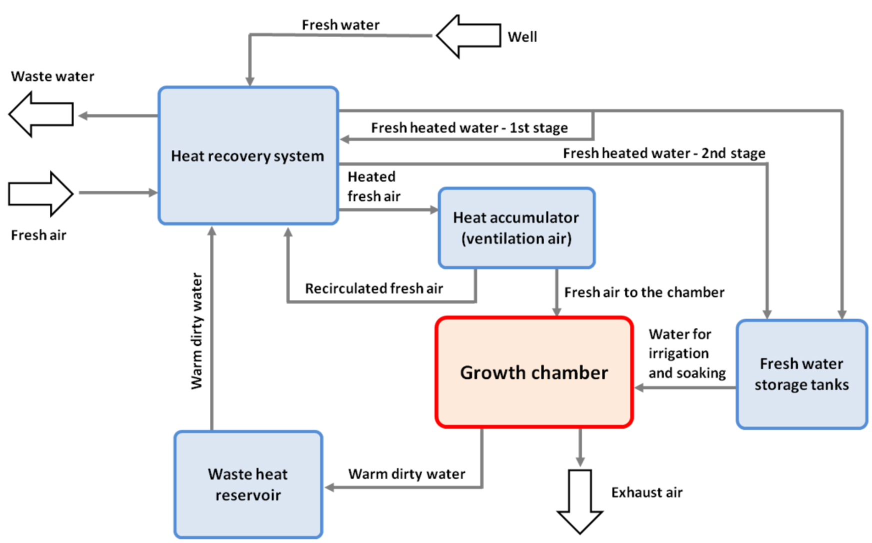

Figure 2: Block diagram of the installation for the production of the mung bean vegetable sprouts with the growth chamber being the subject of the analysis.

ventilating the chamber with the fresh air and supplying the fresh water necessary for the phase of soaking the seeds and irrigation of plant mass. The heat contained in the drainage water from the chamber is recovered in the heat recovery system, whose main task is to heat up the cold water supplied from the deep well.

2.1 Mass balance

From the point of view of mass balance, the growth chamber is a control volume in which optimal conditions for plant growth are ensured by supplying both water and air at a certain temperature. Considering a non-steady flow process for a control volume in a time interval from t_1 to t_2 a balance of mass can be written in general form as [37]

$$\sum m_{\mathrm{in}} - \sum m_{\mathrm{out}} = m_2 - m_1 \,, \tag{3}$$

where m_2 and m_1 denote the amounts of mass in the control volume at the time t_2 and t_1 respectively, and m_{in} and m_{out} represent amounts of mass that enter and leave the control volume given by the following equations:

$$m_{\mathrm{in}} = \int_{t_1}^{t_2} \rho v A \, dt, \tag{4}$$

$$m_{\mathrm{out}} = \int_{t_1}^{t_2} \rho v A \, dt. \tag{5}$$

The left side of Eq. (3) represents the net amount of mass transferred into the control volume, while the right side represents the amount of mass accumulated within it. The Eq. (3) can be written in the rate form as follows

$$\sum \dot{m}_{\mathrm{in}} - \sum \dot{m}_{\mathrm{out}} = \frac{dm_{\mathrm{CV}}}{dt} \,, \tag{6}$$

where $\dot{m}_{\mathrm{in}}$ and $\dot{m}_{\mathrm{out}}$ denote the rate of mass flow that enters and leaves the control volume.

Figure 3 shows a schematic of the growth chamber with the air and water mass streams.

The mass balance for the air entering and leaving the chamber is defined by the equation

$$\dot{m}_{a_{\mathrm{in}}} = \dot{m}_{a_{\mathrm{out1}}} + \dot{m}_{a_{\mathrm{out2}}} \,. \tag{7}$$

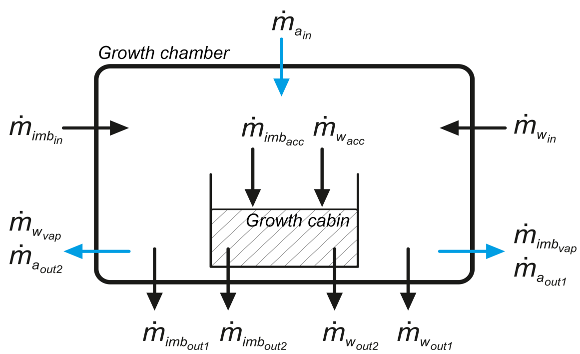

Figure 3: Diagram of the growth chamber with the air and water mass streams entering and leaving the control volume.

The mass balance for water entering and leaving the growth chamber during the imbibition process is given by the equation

$$\dot{m}_{\text{imb}_{\text{in}}} = \dot{m}_{\text{imb}_{\text{out}}} + \dot{m}_{\text{imb}_{\text{acc}}} + \dot{m}_{\text{imb}_{\text{vap}}} \,. \tag{8}$$

The mass balance for water entering and leaving the growth chamber during the plant irrigation process is determined by the equation

$$\dot{m}_{w_{\text{in}}} = \dot{m}_{w_{\text{out}}} + \dot{m}_{w_{\text{acc}}} + \dot{m}_{w_{\text{vap}}} \,. \tag{9}$$

As the stream of water supplied from the sprinkler system does not fully reach the growth cabins, part of the water supplied in the process of imbibition and growth is drained directly to the outlet channel. Therefore, it can be written

$$\dot{m}_{\text{imb}_{\text{out}}} = \dot{m}_{\text{imb}_{\text{out1}}} + \dot{m}_{\text{imb}_{\text{out2}}} \,, \tag{10}$$

$$\dot{m}_{w_{\text{out}}} = \dot{m}_{w_{\text{out1}}} + \dot{m}_{w_{\text{out2}}} \,. \tag{11}$$

Finally, the growth chamber mass balance can be expressed by the following equation

$$\dot{m}_{a_{\text{in}}} + \dot{m}_{\text{imb}_{\text{in}}} + \dot{m}_{w_{\text{in}}} - \left(\dot{m}_{a_{\text{out1}}} + \dot{m}_{a_{\text{out2}}}\right) - \left(\dot{m}_{\text{imb}_{\text{out}}} + \dot{m}_{\text{imb}_{\text{vap}}}\right) - \left(\dot{m}_{w_{\text{out}}} + \dot{m}_{w_{\text{vap}}}\right) = \dot{m}_{\text{imb}_{\text{acc}}} + \dot{m}_{w_{\text{acc}}} \,. \tag{12}$$

2.2 Energy balance

Energy can be transferred to or from a control volume in the forms of heat, work, and mass. Noting that the net transfer of a quantity is equal to the difference between the amounts transferred in and out, the energy balance can be written in general form as follows

$$E_{\text{in}} - E_{\text{out}} = (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass,in}} - E_{\text{mass,out}}) = \Delta E_{\text{CV}} . \tag{13}$$

The amount of energy transport by mass is given by equation

$$E_{\text{mass}} = m\left(h + \frac{v^2}{2} + gz\right) . \tag{14}$$

When the kinetic and potential energies of a fluid stream are negligible and the work done by a system is zero, as is in the case of the growth chamber, the relation (13) simplifies to

$$\Delta E_{\text{CV}} = \Delta Q + \sum m_{\text{out}} h_{\text{out}} - \sum m_{\text{in}} h_{\text{in}} , \tag{15}$$

where in

$$\sum m_{\text{in}} = m_{a_{\text{in}}} + m_{\text{imb}_{\text{in}}} + m_{w_{\text{in}}} , \tag{16}$$

$$\sum m_{\text{out}} = m_{a_{\text{out1}}} + m_{a_{\text{out2}}} + m_{\text{imb}_{\text{out}}} + m_{\text{imb}_{\text{vap}}} + m_{\text{imb}_{\text{acc}}} + m_{w_{\text{out}}} + m_{w_{\text{vap}}} + m_{w_{\text{acc}}} . \tag{17}$$

ΔQ is the change in heat in the control volume due to heat transmission through the chamber walls, the endothermic process of water evaporation, and the exothermic process of plant cellular respiration. A schematic of the growth chamber is shown in Fig. 4, highlighting the heat and energy transported by air and water to and from the control volume.

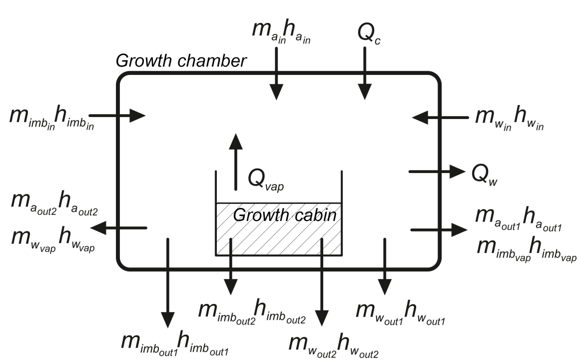

Figure 4: Diagram of the growth chamber with heat and energy transported by air and water to and from the control volume.

The heat supplied to the growth chamber comes from external and internal sources. The transport of heat from the internal source is related to the exothermic process of cellular respiration of germinating plants, while the transport from the external source takes place in the process of heat transmission through a wall. In the same process, heat from the growth chamber is transported to the outside. An additional source of loss is the process of water evaporation during both the imbibition and irrigation phases of the plants. The main mechanism of energy transport to the control volume is the mass flow of air and soaking water. On the other hand, the energy derived from the control volume is associated with the flow of water coming from the sprinkler system, water after the soaking phase, and water absorbing heat from the plant mass contained in the growth cabins. In the further part of the paper, it is assumed that the energy fluxes entering the control volume will be treated as positive and those leaving as negative.

3 Research object

The experimental studies were carried out in the growth chamber of the mung bean sprouts shown in Fig. 5. Depending on the cultivation conditions, i.e. the climatic conditions in the growth chamber, the production period of the mung bean vegetable sprouts lasts from 5 to 7 days and begins with seed disinfection. The first phase of production is the imbibition process. The actual growth stage takes place several hours later giving rise to cyclic phases of watering the plants. Their purpose is to provide the necessary water for germinating seeds and to remove the excess heat generated

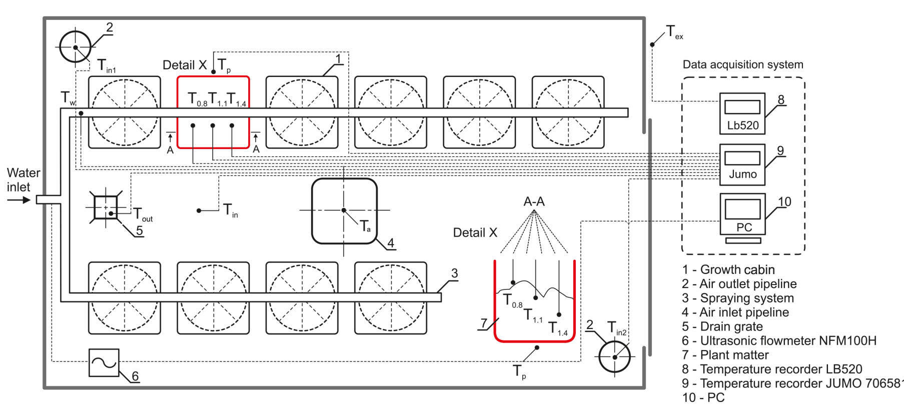

Figure 5: Diagram of the growth chamber of the mung beans.

by the plants in the process of cellular respiration. This heat is a source of low-temperature energy that can be used to increase the efficiency of the production process. In order to avoid excessive heat loss, the chamber is a well-insulated and sealed room equipped with two installations: air and water. The sprouts grow in cabins 1. Gas exchange and oxygen supply are carried out utilizing an inlet 4 and two outlet pipelines 2. The air exchange installation cooperates with two exhaust fans, which are turned on at set intervals and supply air to the chamber. The water installation consists of a sprinkler system 3 supplying water during the soaking and watering phases. This system is integrated with the used water discharge system 5 cooperating with the heat recovery installation. The operation of the soaking and watering installation has been programmed to allow for optimal plant growth conditions.

The aim of the experimental study was to determine the energy streams supplied, withdrawn and generated in the growth chamber during the entire production process. Therefore, during the measurements, the following process parameters were analyzed:

- outlet air temperature in pipelines 1 and 2, respectively – $T_{\text{in}1}$ and $T_{\text{in}2}$,
- inlet air temperature – T_a,
- average air temperature in the growth chamber – T_{in},
- outside air temperature on the front door side – T_{ex},
- volume flow of water for plant watering and spraying,
- irrigation water temperature – T_w,
- temperature of used water discharged directly from the growth cabin – T_p,
- used water temperature measured at the drain – T_{out},
- temperature of sprouts in the cabin $T_{1.4}$, $T_{1.1}$ and $T_{0.8}$ at heights 1.4, 1.1 and 0.8 m, respectively.

The water volume flow was measured on the pipeline supplying water to the sprinkler system using a non-invasive ultrasonic flow meter 6 of the NFM100H type. The signal from the flow meter was recorded with a frequency of 1 Hz. Air temperatures $T_{\text{in}1}$, $T_{\text{in}2}$, T_a and T_{in} were recorded with the same frequency. For this purpose, resistance sensors type TP-366Pt1000 were used. The signals of the sensors were recorded using the JUMO 706581 recorder, providing a maximum sampling frequency of 8 kHz. The device also recorded the water temperature T_w, the temperatures $T_{1.4}$, $T_{1.1}$, and $T_{0.8}$ in the growth cabin, as well as the temperature of used water T_{out} and T_p. Measurement of these parameters was carried out using resistance sensors TP-366Pt100. To eliminate additional resistance of connection cables, all temperature sensors were connected to the JUMO 706581 recorder using four-core silicone compensating cables. The air temperature T_{ex} in the room on the other side of the front wall of the growth chamber was measured with the use of the LB 520 recorder. The measurement system prepared in this way allowed to determine heat fluxes and energy transported by air and water to the growth chamber, including:

- energy transferred in the gas phase by convection mixing – $E_{a_{\mathrm{con}}}$,
- heat coming from the heat storage through the heat transmission – Q_c,
- energy supplied to the growth chamber during the imbibition phase – E_{imb},

as well as heat and energy flows from the growth chamber, including:

- heat exchanged in the gas phase by heat transmission through the front wall of the chamber – Q_{wall},
- energy contained in the imbibition water, which is discharged through a leak to the drain collector – E_d,
- energy contained in the irrigation water, which is discharged through a leak to the drain collector – E_{ds},
- heat needed to evaporate the moisture – Q_{vap}.

In addition to the above-mentioned heat and energy sources, the energy E_s contained in the water flowing through the plant mass in the irrigation process was also determined.

4 Measurement results

The balancing of heat transport in the growth chamber requires the analysis of energy streams exchanged during both soaking and watering phases. These streams occur between the phases air-air, water-air, and water-water and can be determined by measuring the volume flows and the temperature of the air and water supplied to and discharged from the growth chamber.

Proper growth and development of plants depend primarily on ensuring adequate gas exchange. In order to supply the seeds with oxygen and to remove the carbon dioxide produced by the sprouts, it is necessary to ventilate the growth chamber periodically. The source of a fresh air in the process under investigation is the heat store located in the supra chamber space. Figure 6 shows the time courses of air temperatures recorded in the growth chamber, the heat store, and the space on the other side of the front wall. Due to the terms of the agreement on the protection of process data between Czestochowa University of Technology and Uniflora Sp. z o.o., all measurement results have been referred to the maximum values, which are indicated on the diagrams by an apostrophe next to each of the measured values.

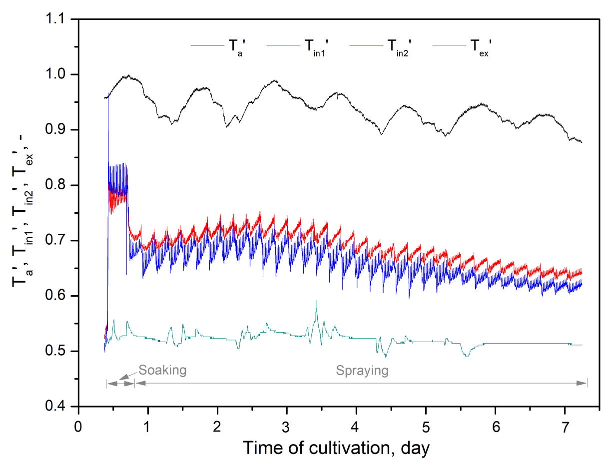

Figure 6: Air temperature time courses recorded in the heat store, the growth chamber, and the space on the other side of the front wall (the designations are taken in accordance with Fig. 5).

Analyzing the course of internal temperature changes in the growth chamber, one can notice their characteristic 'sawtooth' shape. It is an effect of cyclic temperature changes resulting from the periods of plant watering. The maximum temperature values occur at the end of the soaking phase and between the second and third day of the watering phase. As can be seen from the recorded data, to ensure the required conditions for plant growth, the temperature of the supplied air must be 30% to 50% higher than the temperature in the chamber. This difference is needed to cover the losses associated with heat transfer through the walls as well as water evaporation. Figure 7 shows the changes in internal temperature and relative humidity in the growth chamber for selected three consecutive plant watering cycles.

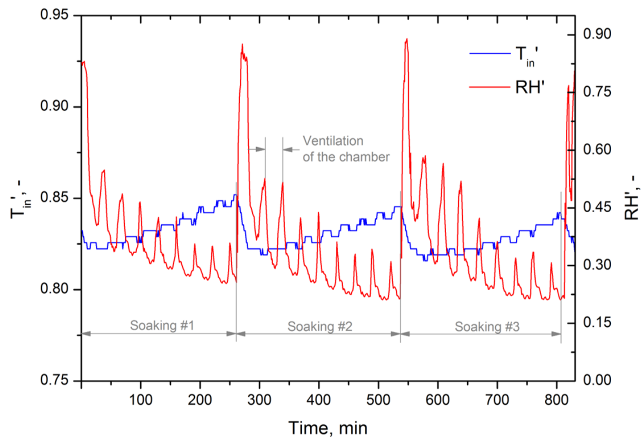

Figure 7: Time series of air temperature (T'_{in}) and humidity recorded (RH′) in the growth chamber for selected three consecutive plant irrigation cycles.

Since the irrigation phase is a cooling process for the plant mass, it is accompanied by a rapid decrease in the air temperature in the chamber. In the period between successive irrigation phases, the air temperature fluctuates periodically with a noticeable upward tendency. Periodic temperature increases are the result of the cyclic supply of air, while decreases are related to the process of intensive evaporation, which is the result of supplying air with a very low relative humidity, not exceeding 10%. As a consequence, in the growth chamber, intensive relative humidity fluctuations within the range from 0.16 to 1 are observed.

The second essential factor for proper plant growth and development is water. Figure 8 shows the time series of soaking, irrigation, and drainage water temperatures recorded in the growth chamber during the imbibition and germination phases. As can be seen, the nature of the changes in this parameter fully coincides with the changes in air temperature. In each of the recorded irrigation cycles the drain water stream T'_p has a temperature higher than the temperature of water for irrigation T'_w. This means that the irrigation phase is not only a process that provides the substrate necessary for growth, but also allows for the reception of heat generated by germinating plants.

The maximum amount of heat generated by the plants occurs between the second and third day. During this period, the difference between the ir-

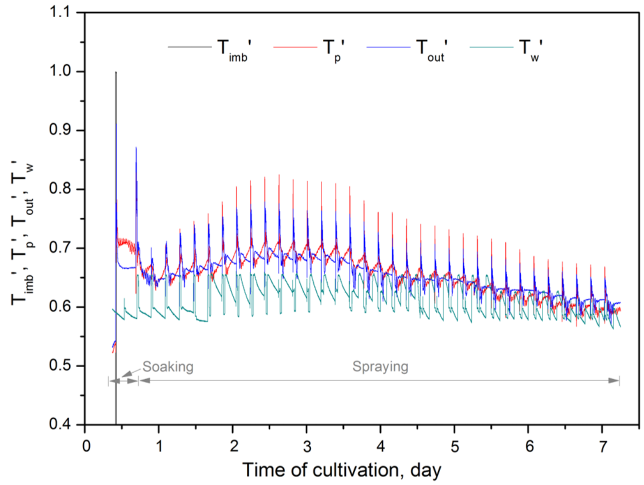

Figure 8: Time series of temperature of soaking, irrigation and drain water recorded in the growth chamber.

rigation and seepage water temperatures exceeds 20%, and at the beginning and the end of the growth cycle, these values are 3% and 9%, respectively.

5 Analysis of measurement results

The main goal of thermodynamic analysis of technological processes is usually to carry out a substance, energy or exergy balance calculation, which covers the whole technological process. In the case analyzed here, this objective is defined somewhat differently as determining the amount of heat generated in the plant growth process, i.e., the energy gain from plant mass production. As the result of such an analysis depends on the location of the balance shield of the system, in the case under consideration it was assumed that the plant growth chamber would be covered by this shield.

In the initial phase of plant growth, the dominant energy process is the convective exchange of energy between the air supplied to the chamber from the external heat store and the internal air. This process is periodic and takes place every few tens of minutes from the soaking phase to the full sprout growth phase. The total amount of heat transferred in the gas phase by convective mixing is given by

$$E_{a_{\rm con}} = V_a \rho_a c_a \big|_{T_{\rm in}}^{T_a} \left(T_a - T_{\rm in}\right), \tag{18}$$

where $c_a\big|_{T_{\rm in}}^{T_a}$ is average specific heat in the given temperature range determined by the relationship

$$c_a\big|_{T_{\rm in}}^{T_a} = \frac{c_a\big|_0^{T_a} T_a - c_a\big|_0^{T_{\rm in}} T_{\rm in}}{T_a - T_{\rm in}} \,. \tag{19}$$

Although the energy supplied to the growth chamber with air allows the internal temperature to remain stable, as can be seen from Fig. 6, its value must be large enough to cover the losses associated with the phase change of the water and heat transfer by thermal conduction. The total amount of heat required for the water phase change can be determined from equation

$$Q_{\rm vap} = V_a \rho_a \frac{\Delta H_{\rm vap}}{\mu_w} \,. \tag{20}$$

The heat $Q_{\rm vap}$ depends not only on the air temperature but primarily on the relative humidity gradient. Therefore, taking into account the dynamic changes of humidity occurring in the growth chamber, the values of this heat are subject to very intensive changes throughout the production cycle.

As the warm air store is located in the direct vicinity of the growth chamber, an additional source of energy is the heat continuously flowing through the wall separating the two rooms. The amount of heat transported along the path of transmission can be determined from the relationship

$$Q_c = \frac{1}{\dfrac{1}{\alpha_{\rm ex\_\mathit{v}}} + \dfrac{d_1}{\lambda_1} + \dfrac{d_2}{\lambda_2} + \dfrac{1}{\alpha_{\rm in\_\mathit{v}}}} A_c t \left(T_a - T_{\rm in}\right), \tag{21}$$

where the subscripts 1 and 2 indicate wall partition number.

Apart from the heat stream penetrating the ground, the main source of losses of the growth chamber is the room located on the other side of the front wall. This wall is built of the same partition materials as the wall bordering the heat store. The amount of heat transported outside is determined by the relation

$$Q_w = \frac{1}{\dfrac{1}{\alpha_{\rm ex\_\mathit{h}}} + \dfrac{d_1}{\lambda_1} + \dfrac{d_3}{\lambda_2} + \dfrac{1}{\alpha_{\rm in\_\mathit{h}}}} A_F t \left(T_{\rm ex} - T_{\rm in}\right), \tag{22}$$

where the subscripts 3 indicate wall partition number.

Figure 9 shows a Sankey diagram of the different types of heat entering and leaving the growth chamber with the air.

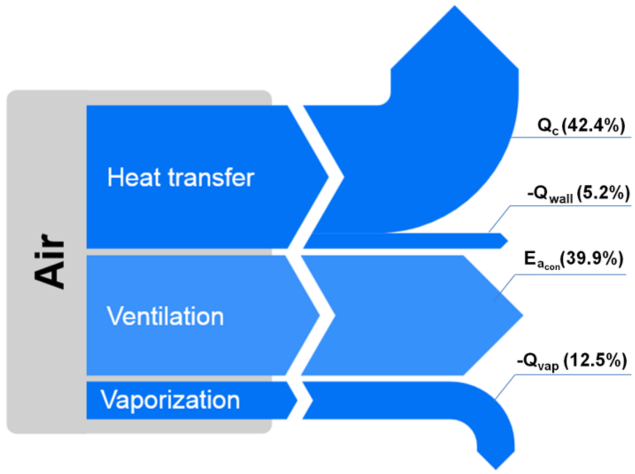

Figure 9: Sankey diagram of the different types of heat entering and leaving the growth chamber with air.

As shown in the figure, the energy sources for the growth chamber are heat transfer (42.4%) and warm air transport (39.9%) from the heat storage. However, the sources of losses are the front wall (5.2%) and the processes associated with moisture evaporation (12.5%). The balance does not take into account the losses due to heat transfer through other walls, which results from a negligibly small value of the temperature gradient. Air-to-air and air-to-water heat exchanges occur during both the soaking and irrigation cycles of the plants. Since the total amount of heat supplied with air and required for optimum plant growth conditions comes from external sources, the overall balance of the chamber will represent an energy gain. However, from the point of view of the whole technological process, this heat must be produced using an external energy source. Figure 10 shows the distribution of the shares of heat exchanged in the gas phase during the entire plant growth cycle in the growth chamber.

The presented results show that ensuring the required conditions for plant growth through an appropriate gas exchange is associated with significant energy expenditure. In the soaking phase, the energy demand is nearly 43 MJ, while in the irrigation phase as much as 1.17 GJ. It should be noted that the amount of heat supplied to the growth chamber along with the air is slightly greater than the amount of heat supplied due to the heat transfer from the heat store. This is because heat is supplied periodically in the air stream for about 17% of the cycle time, while heat is

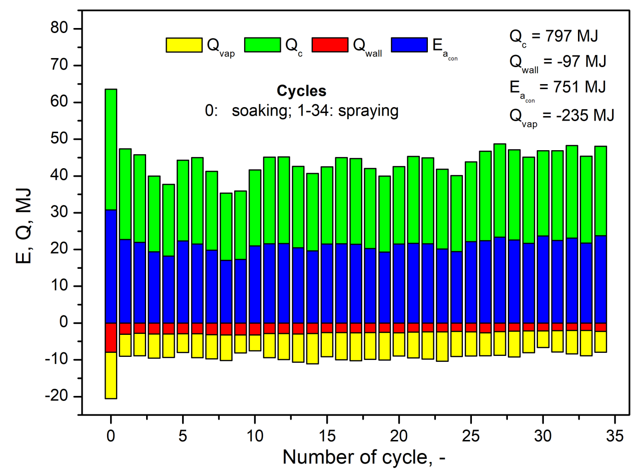

Figure 10: Shares of energy exchanged in the gas phase during the entire plant growth cycle in the growth chamber.

transferred continuously through transmission. The total amount of energy supplied in the gas phase throughout the plant growth cycle is as much as 1.5 GJ.

The second factor that plays a key role in the soaking and irrigation phases of plants is water. It allows seeds to germinate, increase plant mass and collect heat from germinating and growing plants. In the initial soaking phase, the amount of heat supplied to the growth chamber along with the water can be determined by the relationship

$$E_{\text{imb}} = V_{\text{imb}} \rho_w c_w \left(T_{\text{imb}} - T_{\text{ref}} \right). \tag{23}$$

After several hours of imbibition, the heat contained in the water can be determined from the relationship

$$E_d = V_d \rho_w c_w \left(T_p - T_{\text{ref}} \right). \tag{24}$$

Equation (24) determines the heat recovered at the exit of the growth chamber, while the sum of E_{imb} and E_d determines the energy supplied to the growth chamber during the seed imbibition process. In the entire production cycle of the mung bean sprouts, the only complete exoenergetic process occurs during the watering phase. In this phase the total amount of heat is made up of the heat contained in the water of moderate temperate, which goes directly to the output collector during the irrigation process due to leakage, and the heat contained in the water flowing through the plant mass. In the first case, the amount of heat output can be determined from the equation

$$E_{ds} = V_d \rho_w c_w |_{T_w}^{T_{\text{out}}} (T_{\text{out}} - T_w) , \tag{25}$$

while in the second case the amount of recovered heat is determined by the relation

$$E_s = V_s \rho_w c_p |_{T_w}^{T_{\text{out}}} (T_{\text{out}} - T_w) . \tag{26}$$

Figure 11 shows the Sankey diagram for heat supplied and discharged with water from the growth chamber. In the soaking phase, the energy source is warm water supplied from the outside, while in the irrigation phase, the stream of cold water supplied receives energy from the plant mass.

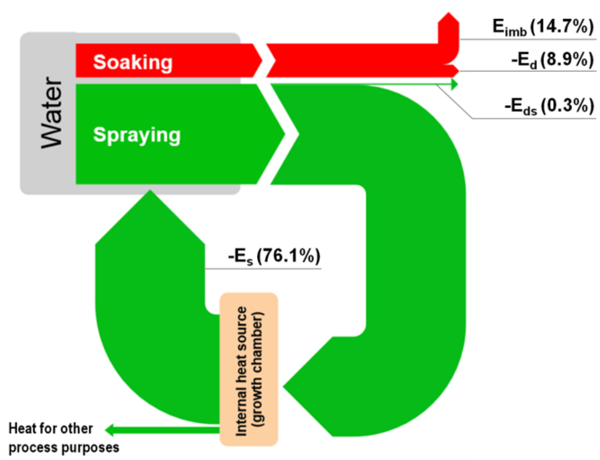

Figure 11: Sankey diagram for heat supplied and discharged with water from the growth chamber.

As plant germination is accompanied by intense heat release, an internal energy source is created in the growth chamber, which allows for effective heating of water that is reused in plant production processes. Figure 12 shows the distribution of the share of heat exchanged in the liquid phase during the entire plant growth cycle in the growth chamber.

This distribution throughout the production cycle is an uneven one due to the nature of the heat generated by the sprouts. This heat in the process of biological mass growth is generated exclusively by nutrients stored in the seeds and reaches a maximum between the eleventh and sixteenth irrigation cycles (245 MJ). From the seventeenth cycle onwards, the amount of heat

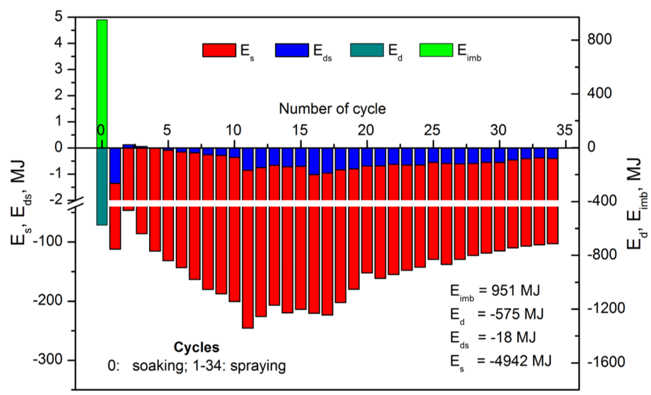

Figure 12: Shares of heat exchanged in the liquid phase during the entire plant growth cycle in the growth chamber.

generated decreases, which means that the energy resources necessary for growth are gradually exhausted. Since the cultivation is carried out in total darkness, the plants cannot carry out photosynthesis, from which they derive the energy needed for further growth in the natural environment. The minimum value of energy determined in the growth process is 46 MJ and occurs during the second cycle of irrigation of the plants. In general, in the soaking phase, when the highest temperature water is supplied, the energy input is as high as 951 MJ. Some of this energy can be recovered, bringing the total heat input to 376 MJ. Overall, the total heat generated by the plants during germination is 4942 MJ.

Figure 13 shows the distribution of the shares of energy input (Fig. 13a) and output (Fig. 13b) from the growth chamber. The presented data show that in both cases, the maximum energy values concern the water phase. In the whole growth cycle, the highest amount of heat input is absorbed in the soaking phase (38%). This is the longest and also the most energy-consuming cycle in the sprout production process. On the other hand, taking into account the dissipated energy, the highest value falls on the irrigation phase, in which almost 85% of the heat is removed from the sprout.

Figure 14 shows a summary of the shares of heat exchanged in the gas and liquid phases during the entire plant growth cycle in the growth chamber. The results show that the heat from germinating plants is mainly transferred to the liquid phase during the irrigation process, which makes this phase of plant production an exothermic one. On the other hand, the

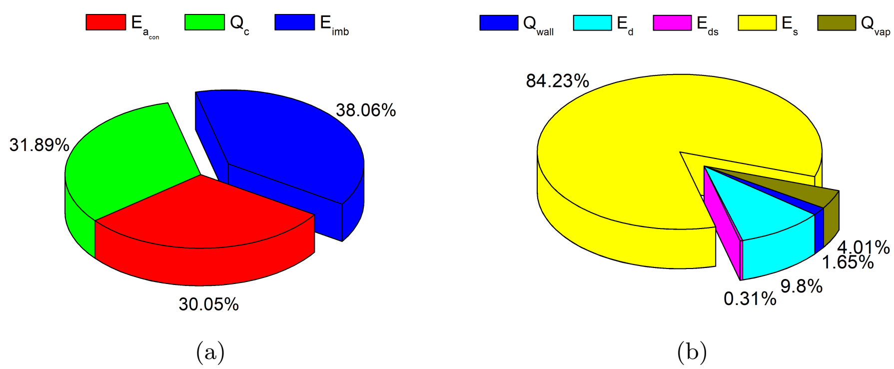

Figure 13: Distribution of heat shares: (a) supplied to the growth chamber; (b) discharged from the growth chamber.

need to ensure gas exchange in the growth chamber involves the supply of a large amount of heat, making this process an endoenergetic process.

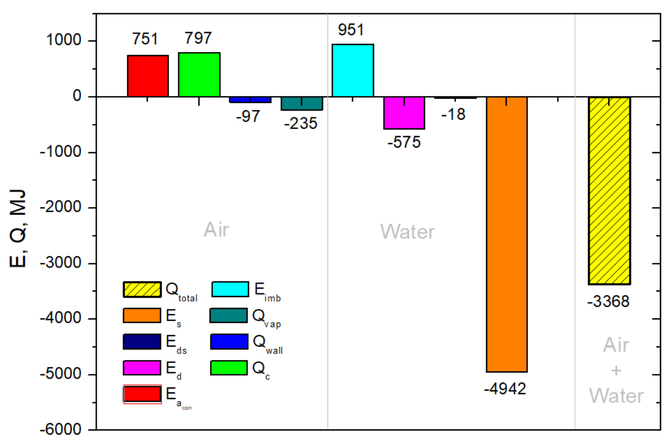

Figure 14: Summary of the heat exchanged in the gas and liquid phase during the entire plant growth cycle in the growth chamber.

The total amount of heat generated by plants in the entire production process is nearly 3.4 GJ. Thus, germinating mung bean seeds provide a significant amount of heat. This energy can be used to prepare the required water and air parameters and contribute to a significant reduction of the energy needs of the production process. Purification and re-use of water used for irrigation can further reduce the over-exploitation of water resources.

6 Summary

The conducted experimental research and the analysis of the obtained results allowed the formulation of the following conclusions:

1. The time distribution of the heat generated by plants throughout the production cycle is non-uniform. This heat in the process of biological mass growth reaches its maximum between the eleventh and sixteenth irrigation cycle (245 MJ) and minimum (46 MJ) in the second cycle.

2. The total amount of gross and net heat generated is 4942 MJ and 3368 MJ, respectively.

3. The maximum amount of heat generated by the plants occurs between the second and third day. During this period, the difference between the temperature of the water entering and leaving the growth cabin exceeds 20%.

4. Taking into account the energy transformations occurring in the growth chamber, ensuring the required conditions for plant growth involves supplying air with a temperature between 30% and 50% higher than the temperature in the chamber. In the soaking phase, the demand for energy supplied with air is nearly 43 MJ, while in the irrigation phase as much as 1.17 GJ.

5. Throughout the growth period, the air and water temperatures discharged from the growth chamber reach their maximum values at the end of the soaking phase and between the second and third day of the irrigation phase.

6. In the entire production cycle of the mung beans, the only complete exoenergetic process occurs during the irrigation phase.

7. The main cause of periodic changes of air temperature in the growth chamber are energy processes occurring during the phase of irrigation of plants and the process of water evaporation resulting from the mixing of air streams with a large difference in humidity.

Taking all into account, it should be stated that a significant amount of low exergy heat is generated in the production process of the mung bean sprouts. The use of this heat in a highly efficient installation built based on plate heat exchangers should allow to significantly reduce not only the energy needs of the production process but also minimize the use of natural water resources.

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References

[1] Szargut J., *et al.*: *Industrial Waste Energy: Principles of Utilization, Equipment.* WNT, Warszawa 1993 (in Polish).

[2] Turner W.C., Doty S., Eds.: *Energy Management Handbook* (6th Edn.). Fairmont Press CRC, Taylor & Francis, Lilburn, Boca Raton 2007.

[3] Firth A., Zhang B., Yang A.: *Quantification of global waste heat and its environmental effects*. Appl. Energ. **235**(2019), 1314–1334. doi: 10.1016/j.apenergy.2018.10.102

[4] Eurostat, 2022. *Energy statistics – an overview*. http://ec.europa.eu/eurostat/statistics-explained/index.php?title= Energy_statistics_-_an_overview#Final_-energy_ consumption (accessed 20 Feb. 2022).

[5] Papapetrou M., Kosmadakis G., Cipollina A., La Commare U., Micale G.: *Industrial waste heat: Estimation of the technically available resource in the EU per industrial sector, temperature level and country*. Appl. Therm. Eng. **138**(2018), 207–216. doi: 10.1016/j.applthermaleng.2018.04.043

[6] *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. BCS Incorporated, 2008. http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf (accessed 26 Sept. 2021).

[7] Fitó J., Hodencq S., Ramousse J., Wurtz F., Stutz B., Debray F., Vincent B.: *Energy- and exergy-based optimal designs of a low-temperature industrial waste heat recovery system in district heating*. Energ. Convers. Manage. **211**(2020), 112753. doi: 10.1016/j.enconman.2020.112753

[8] Xu Z.Y., Wang R.Z., Yang C.: *Perspectives for low-temperature waste heat recovery*. Energy **176**(2019), 1037–1043. doi: 10.1016/j.energy.2019.04.001

[9] Adamkiewicz A., Nikończuk P.: *Waste heat recovery from the air preparation room in a paint shop*. Arch. Thermodyn. **40**(2023), 3, 229–241. doi: 10.24425/ather.2019.130003

[10] Deymi-Dashtebayaz M., Valipour-Namanlo S.: *Thermoeconomic and environmental feasibility of waste heat recovery of a data center using air source heat pump*. J. Clean. Prod. **219**(2019), 117–126. doi: 10.1016/j.jclepro.2019.02.061

[11] Morgan R., Nelmes S., Gibson E., Brett G.: *Liquid air energy storage – Analysis and first results from a pilot scale demonstration plant.* Appl. Energ. **137**(2015), 845–853. doi: 10.1016/j.apenergy.2014.07.109

[12] Strahan D. (Ed.): *Liquid air in the energy and transport systems: opportunities for industry and innovation in the UK.* Rep. 021. Centre for Low Carbon Futures, Brighton 2013.

[13] Loni R., Najafi G., Bellos E., Rajaee F., Said Z., Mazlan M.: *A review of industrial waste heat recovery system for power generation with Organic Rankine cycle: Recent challenges and future outlook.* J. Clean. Prod. **287**(2021), 125070. doi: 10.1016/j.jclepro.2020.125070

[14] Uusitalo A., Honkatukia J., Turunen-Saaresti T.: *Evaluation of a small-scale waste heat recovery organic Rankine cycle.* Appl. Energ. **192**(2017), 146–158. doi: 10.1016/j.apenergy.2017.01.088

[15] Carvajal-Mariscal I., De León-Ruíz J.E., Belman-Flores J.M., Salazar-Huerta A.: *Experimental evaluation of a thermosyphon-based waste-heat recovery and reintegration device: A case study on low-temperature process heat from a microbrewery plant.* Sustain. Energy Technol. Assess. **49**(2022), 101760. doi: 10.1016/j.seta.2021.101760

[16] Zühlsdorf B., Jørgensen P.H., Elmegaard B.: *Industrial Heat Pumps, Second Phase IEA Heat Pump Technology (HPT) Programme Annex 48 Task 1: Danish Report.* Danish Technological Institute (2019). https://orbit.dtu.dk/en/publications/industrial-heat-pumps-second-phase-iea-heat-pump-technology-hpt-p (accessed 19 Feb. 2022).

[17] Song J., Li Y., Gu C., Zhang L.: *Thermodynamic analysis and performance optimization of an ORC (Organic Rankine Cycle) system for multi-strand waste heat sources in petroleum refining industry.* Energy **71**(2014), 673–680. doi: 10.1016/j.energy.2014.05.014

[18] Hu B., Liu H., Jiang J., Zhang Z., Li H., Wang R.Z.: *Ten megawatt scale vapor compression heat pump for low temperature waste heat recovery: Onsite application research.* Energy **238**(2022), 121699. doi: 10.1016/j.energy.2021.121699

[19] Knudsen B.R., Rohde D., Kauko H.: *Thermal energy storage sizing for industrial waste-heat utilization in district heating: A model predictive control approach.* Energy **234**(2021), 121200. doi: 10.1016/j.energy.2021.121200

[20] Wu X., Xing Z., He Z., Wang X., Chen W.: *Performance evaluation of a capacity-regulated high temperature heat pump for waste heat recovery in dyeing industry.* Appl. Therm. Eng. **93**(2016), 1193–1201. doi: 10.1016/j.applthermaleng.2015.10.075

[21] Rakib M.I., Saidur R., Mohamad E.N., Afifi A.M.: *Waste-heat utilization – The sustainable technologies to minimize energy consumption in Bangladesh textile sector.* J. Clean. Prod. **142**(2017), 1867–1876. doi: 10.1016/j.jclepro.2016.11.098

[22] Sekkeli M., Kececioglu O.: *SCADA based an energy saving approach to operation of stenter machine in a textile plant using waste heat recovery system.* Tekstil Ve Konfeksiyon **22**(2012), 3, 248–257.

[23] Skjern Papirfabrik: *Sustainability Report 2018.* Skjern 2018. https://www.skjernpaper.com/media/ehypqkge/06_2191827_rapport_2018_uk.pdf (accessed 13 May 2022).

[24] Mubarak A.E.: *Nutritional composition and antinutritional factors of mung bean seeds (Phaseolus aureus) as affected by some home traditional processes.* Food Chem. **89**(2005), 489–495. doi: 10.1016/j.foodchem.2004.01.007

[25] Bewley J.D., Bradford K.J., Hilhorst H.W.M., Nonogaki H.: *Seeds: Physiology of Development, Germination and Dormancy* (3rd Edn.). Springer, New York 2013.

[26] The European Commission: Commission Implementing Regulation (EU) No 208/2013 of 11 March 2013 on traceability requirements for sprouts and seeds intended for the production of sprouts. Official Journal of the European Union, L 68/16, 12.3.2013.

[27] *ESSA hygiene guideline for the production of sprouts and seeds for sprouting.* European Sprouted Seeds Association (2017). https://op.europa.eu/en/publication-detail/-/publication/4d31413a-63a0-11e7-b2f2-01aa75ed71a1 (accessed 6 July 2022).

[28] Criddle R.S., Breidenbach R.W., Hansen L.D.: *Plant calorimetry: how to quantitatively compare apples and oranges.* Thermochim. Acta **193**(1991), 67–90. doi: 10.1016/0040-6031(91)80175-I

[29] Morohashi Y., Sugimoto M.: *ATP Synthesis in cotyledons of cucumber and mung bean seeds during the first hours of imbibition.* Plant Cell Physiol. **2**9(1988), 5, 893–896. doi: 10.1093/oxfordjournals.pcp.a077578

[30] Thygerson T., Harris J.M., Smith B.N., Hansen L.D., Pendleton R.L., Booth D.T.: *Metabolic response to temperature for six populations of winterfat (Eurotia lanata).* Thermochim. Acta **394**(2002), 211–217. doi: 10.1016/S0040-6031(02)00253-8

[31] Skoczowski A., Troć M.: *Isothermal calorimetry and raman spectroscopy to study response of plants to abiotic and biotic stresses.* In: Molecular Stress Physiology of Plants (G.R. Rout, A.B. Das, Eds.), 263–288. Springer, New Delhi 2013. doi: 10.1007/978-81-322-0807-5_11

[32] Pierce G.J.: *A new respiration calorimeter.* Bot. Gaz. **46**(1908), 193–202. doi: 10.1086/329696

[33] Schabes F.I., Sigstad E.E.: *Is it possible to determine physiological quality and best conditions of storage of soybean seeds by isothermal calorimetry?* Thermochim. Acta **579**(2014), 45–49. doi: 10.1016/j.tca.2014.01.014

[34] Stawoska I., Staszak A.M., Ciereszko I., Oliwa J., Skoczowski A.: *Using isothermal calorimetry and FT-Raman spectroscopy for step-by-step monitoring of maize seed germination: case study.* J. Therm. Anal. Calorim. **142**(2020), 755–763. doi: 10.1007/s10973-020-09525-x

[35] Sigstad E.E., Prado F.E.: *A microcalorimetric study of Chenopodium quinoa Willd. seed germination.* Thermochim. Acta **326**(1999), 159–164. doi: 10.1016/S0040-6031(98)00599-1

[36] Sigstad E.E., Schabes F.I., *Isothermal microcalorimetry allows detection of 'aquaporines' in quinoa seeds.* Thermochim. Acta **349**(2000), 95–101. doi: 10.1016/S0040-6031(99)00501-8

[37] Dincer I., Rosen M. A.: *Exergy. Energy, Environment and Sustainable Development* (1st Edn.). Elsevier Sci., 2007.