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PhD Thesis

The utilization of low-exergy heat from the vegetable sprouts production process

SUMMARY

INTRODUCTION

Progressive climate change, environmental degradation, and the depletion of traditional fossil fuel reserves represent formidable global challenges. To confront these pressing issues, the European Union, including Poland, has directed its efforts toward reducing greenhouse gas emissions, expanding the utilization of diverse renewable energy sources, and enhancing overall energy efficiency. Within both EU and Polish climate and energy policies, the pursuit of energy efficiency plays an important role. One effective approach to improve energy efficiency involves further harnessing energy in the form of waste heat, which typically accompanies most energy transformations but is often dismissed as a by-product.

The amount of waste heat resources that can be economically utilized is estimated at around 16% of the more than 50% energy loss that occurs in total global energy consumption. Focusing solely on the industrial sector, development of this potential could result in annual energy savings of approximately 4.11 PWh. In the case of Poland, the theoretical potential of waste heat is estimated to be around 43.6 TWh. Unfortunately, activities related to tapping into these substantial waste energy resources have received marginal attention thus far. Paradoxically, more emphasis has been placed on advancing energy extraction and transformation technologies than on its recovering and reusing. Although the use of such a huge amount of available energy can bring a number of benefits in the form of:

- enhanced energy efficiency,
- improved economic indicators,
- reduced environmental impact, as well as

- increased the public trust of manufacturing companies.

The primary source of industrial waste heat is low-temperature waste heat, which often presents two significant challenges: low exergy of the medium and high levels of source dissipation. In cases where dissipation isn't a major hurdle, leveraging waste energy can make a substantial contribution to process efficiency. An example of such a process is seed germination.

In the course of their growth, germinating plants produce a flow of low-temperature heat (20-40°C), which dissipates into the environment and is traditionally lost irreversibly in standard production systems. This heat generation in plants is directly linked to metabolic processes, particularly cellular respiration. As a by-product of the reactions occurring during this process, heat is released and disperses into the surroundings. In controlled cultivation settings, there is an opportunity to capture and utilize this heat in the plant production process. Given that the heat generated by germinating plants is of relatively low quality, the cost-effectiveness of such an operation primarily hinges on the magnitude of the available heat resource and the technical feasibility of its recovery. In this context, a critical challenge lies in accurately estimating the heat flow produced by germinating seeds, both in laboratory conditions and on production lines, to gauge the possible and actual potential of heat recovery from germinating plants. The possible potential can be assessed through microcalorimetric studies. However, conducting studies on living plant organisms is difficult and demands specific measurement conditions, including ensuring gas exchange, providing access to water, and maintaining suitable microclimatic conditions. These conditions can be met by employing specialized ultra-sensitive calorimetric devices capable of continuous heat generation measurement over a period of several hours. The most commonly utilized device for this purpose is the isothermal microcalorimeter. Determining the actual potential for heat recovery necessitates comprehensive tests on the production line. Estimating this potential, coupled with knowledge of the sprout production technology, enables the practical utilization of energy generated by plants to be ascertained. Up until now, there have been no documented efforts in the literature to estimate the potential for heat recovery from germinating seeds. Moreover, any previous measurements of plant metabolic heat have leaned towards biological analyses rather than thermodynamic assessments.

THESIS, OBJECTIVES AND SCOPE

In accordance with the literature review, the following theses of the PhD dissertation are formulated:

1. Biological processes taking place during the cultivation of vegetable sprouts can be a source of significant resources of low-temperature waste heat.
2. It is possible to reduce the energy intensity and consumption of conventional fuels in a installation for the production of vegetable sprouts for food by using waste heat generated by plants.

The objective of this dissertation is to investigate waste heat resources within the growth process of selected plants, namely mung beans and sunflowers. The primary goal is to develop an effective method for managing the waste heat generated during sprout growth, ultimately enhancing the overall production process efficiency. This research encompasses various key aspects: determining the fundamental technical parameters of mung bean and sunflower seeds, conducting calorimetric tests to assess the possible potential for heat recovery from sprouting plants at a micro-scale level, performing measurements on a vegetable sprout production line to ascertain the actual heat recovery potential at a macro-scale, conducting a comprehensive mass, energy, and exergy balance analysis of the growth chamber, analyzing the potential for reducing the energy intensity of the vegetable sprout production process for food use and developing a simulation model for a technological production line for sprouts, including an integrated heat recovery system from sprouting seeds.

METHODS

The determination of waste heat resources in the cultivation of mung bean sprouts and sunflower requires, firstly, the determination of the specific heat flow generated throughout the growth process by these plants under laboratory conditions, as well as an estimation of the possible heat recovery potential from the germinating seeds. This research utilizes a TAM III isothermal microcalorimeter from TA Instruments, equipped with two 20 ml vessels: a measuring vessel and a reference vessel. Stainless steel vessels, featuring perforated lids, are selected for measurements to ensure unimpeded oxygen access for the seeds and the removal of carbon dioxide. To maintain comparability between micro and macro-scale results, the measurement procedure is designed to closely replicate production line conditions. Consequently, the investigation into the specific heat generated by both plants during germination and growth is divided into two phases: the soaking phase and the growth phase. These phases are executed at distinct temperatures, with each temperature change necessitating instrument calibration. A diagram showing the successive stages of the research procedure is shown in Figure 1. Due to confidentiality agreement outlined in the data protection terms between Czestochowa University of Technology and Uniflora Sp. z o.o., specific details regarding the measurement temperatures employed in this dissertation cannot be disclosed.

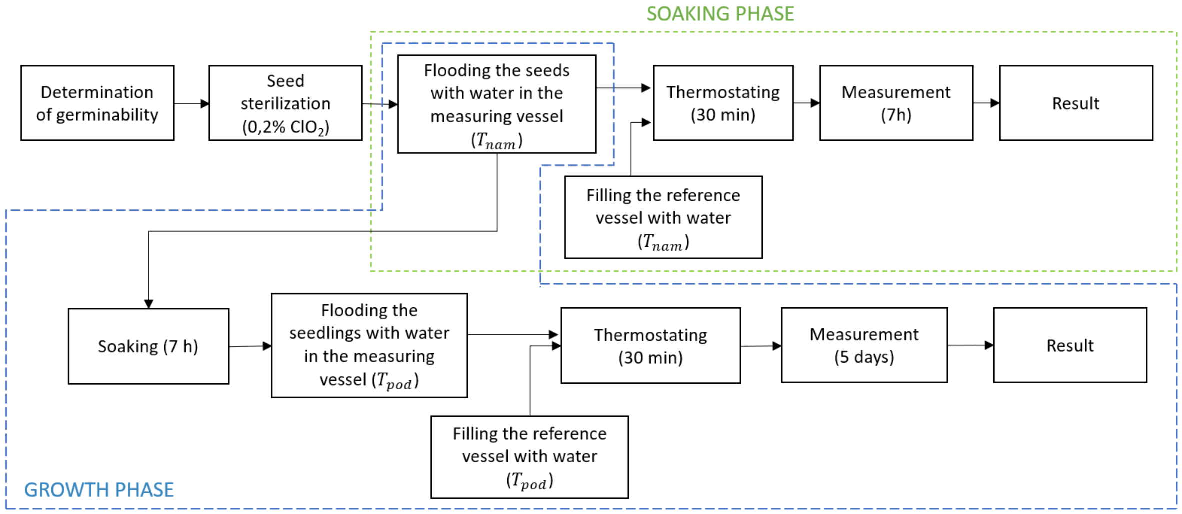

Figure 1 Schematic diagram of the test procedure for determining the heat flux generated by mung bean and sunflower seeds during germination and growth using a TAM III isothermal microcalorimeter (T_{nam} – soaking temperature, T_{pod} – watering temperature).

Determining the actual heat recovery potential from germinating mung bean seeds necessitates measurements on a vegetable sprout production line. The vegetable sprout production period spans 5 to 7 days, contingent on the cultivation conditions, specifically the climatic factors within the growth chamber. The cultivation process commences with seed disinfection, followed by a soaking phase in warm water lasting approximately 7 hours. Subsequently, the actual sprout growth phase begins, requiring cyclic watering. This serves a dual purpose: supplying the plants with essential water for growth and dissipating the excess heat generated by plant cells as a consequence of metabolic reactions.

This heat is a source of low-temperature energy that can be used to increase the efficiency of the production process. The primary experimental research unfolds within a growth chamber designed for industrial mung bean sprout cultivation intended for food consumption. This chamber comprises cabins where sprout growth occurs. Effective germination and subsequent plant development hinge predominantly on maintaining adequate gas exchange and water accessibility. To address these requirements, the chamber is outfitted with two systems: an air system and a water system. To ensure the seeds receive oxygen and to eliminate the carbon dioxide produced by the sprouts, periodic room ventilation is necessary, drawing air from a heat reservoir located in the chamber's headspace. The water system consists of a spraying system supplying water during the soaking and watering phases. This system is integrated with the waste water drainage system. Experimental research on the production line span the complete 7-day mung bean sprout production cycle. To estimate the actual potential of heat recovery from the plants, it is imperative to determine the energy flows entering, exiting, and generated within the growth chamber. As a result, the measurements encompass monitoring various parameters, including:

- the temperature of the exhaust and supply air to and from the growth chamber,
- the air temperature within the growth chamber,
- the external air temperature,
- the volume flow rate of water delivered to the plants,
- the temperature of the watering water,
- the discharged used water directly from the cabins,
- the collected used water measured in the drain,
- the temperature of the sprouts.

To illustrate the potential for reducing energy and conventional fuel usage in a vegetable sprout production facility by harnessing the waste heat produced by the plants, a system concept for heat recovery from the sprouts is devised. Additionally, a simulation model for a comprehensive sprout production line, integrated with the proposed heat recovery system, is developed. The possibility of reducing the plant's energy consumption is assessed through transient simulation calculations conducted within the FLOWNEX® simulation environment. Figure 2 presents a block diagram outlining the concept of utilizing waste heat generated during the biological processes of sprout growth to produce fresh water for watering crops.

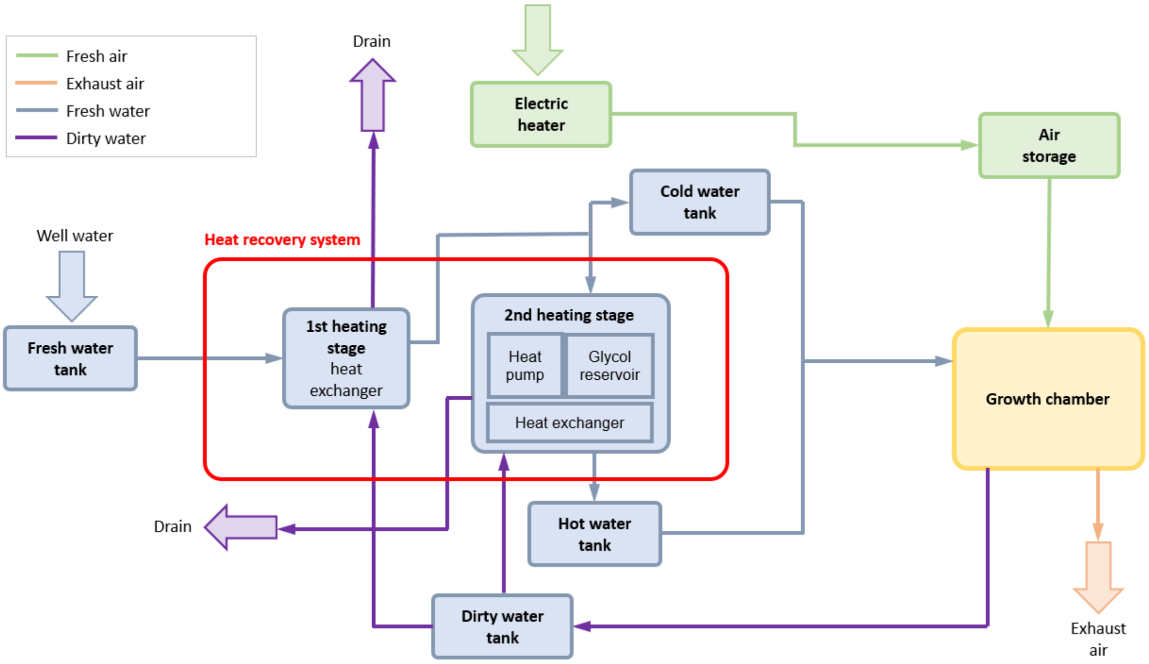

Figure 2 Schematic block diagram of a installation for the production of Mung bean vegetable sprouts with heat recovery.

The proposed concept for preparing fresh water using waste heat is implemented in two stages. Fresh water from a deep well is preheated in a heat exchanger (1st stage of heating) using dirty water at a higher temperature from watering the sprouts. Part of the preheated water is then directed to the cold water tank, while the remainder moves to the second stage. In the 2nd stage of heating, a compressor heat pump, a glycol reservoir, and a heat exchanger are used to further heat the fresh water to a temperature higher than that required for watering. This heated water goes to the hot water tank, and both hot and cold water are mixed in the appropriate proportions to provide the desired temperature for watering the sprouts. After watering, the dirty water goes into the dirty water tank, where it is used in a heat recovery system to heat fresh water from the well. By using this configuration, the heat stored in the water after watering the plants can be maximally utilized. As part of the analysis of the possibility of heat recovery from the vegetable sprout production process, a series of simulation experiments of the full transient production cycle are carried out for various production scenarios.

RESULTS OF CALORIMETRIC RESEARCH

The total heat flow generated throughout the soaking and growth phases of mung bean sprouts (over a 5-day period) falls within the range of 1712 to 3135 J/g_{seed} at a 95% confidence level. Figure 3 illustrates the specific thermal power, representing the average heat flow observed during measurements in both the soaking stage (a) and the growth stage (b). During the soaking phase, the heat flow gradually increases until it reaches its peak (approximately 2500 μW), after which it decreases to approximately 500 μW. The average heat energy generated during the soaking phase, at a 95% confidence level, falls between 22.36 and 24.49 J/g_{seed}. The source of the heat emitted during this germination phase is physical processes, i.e. the imbibition process (rapid hydration of colloids in the seed) and the accompanying mechanical stresses that occur in the seed coat. In the sprout growth phase, the average heat generated ranges from 1689.72 to 3132.18 J/g_{seed} at a 95% confidence level. The metabolic activity of the seed increases until approximately the 50th hour of the growth phase when the plant reaches a maximum energy flow of approximately 7500 μW. It then gradually decreases and stabilizes at 5500 μW.

The effects of the soaking phase are a cracked seed coat and sprouting embryonic roots, while the growth phase results in properly formed sprouts. Given that these outcomes align with those achieved through controlled cultivation, it can be concluded that the TAM III microcalorimeter serves as a tool capable of determining the heat flow generated by germinating plants.

In contrast to mung bean seeds, sunflower seeds show germination problems under microcalorimetric conditions, which could be observed during both the soaking and growth phases. These issues manifest during both the soaking and growth phases, resulting in improper germination and a lack of germination signs in most seeds within the sample. Assessing the heat flow generated by sunflower seeds presents several biological and instrumental challenges that surpass the scope of this dissertation. Considering the difficulties encountered in this study, it can be stated that contemporary microcalorimetric equipment does not allow a comprehensive analysis of the heat flow generated by naturally occurring sunflower seeds during both the soaking and sprout growth phases. Consequently, the determination of the possible and actual potential waste heat recovery from germinating plants is confined to the examination of mung bean seeds.

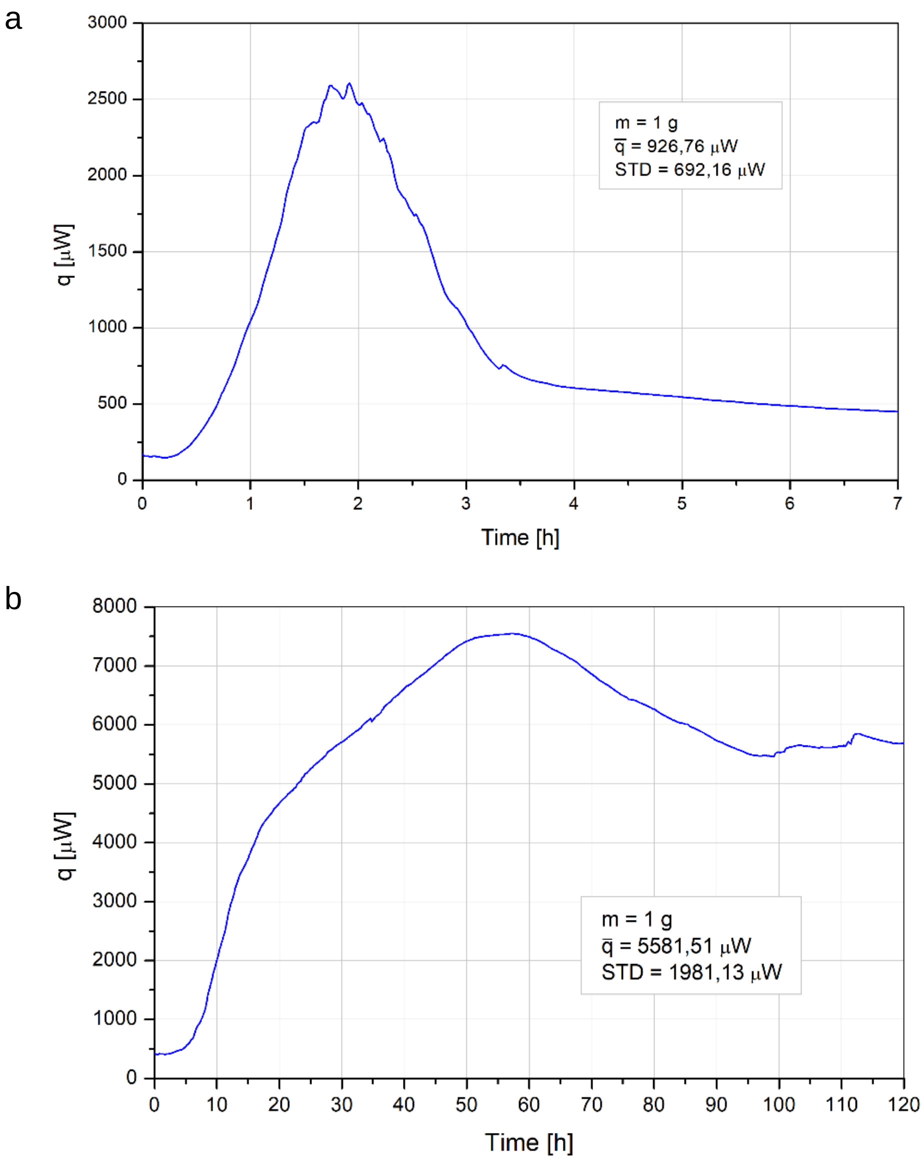

Figure 3 Specific thermal power generated by Mung bean seeds during soaking (a) and growth (b).

RESULTS OF THE SPROUT PRODUCTION LINE RESEARCH

The production process encompasses two distinct stage: soaking and growth. Within these stages, a distinction arises between a gas phase associated with fresh air introduction into the growth chamber and a liquid phase resulting from the watering process. In the gas stage, the growth chamber's energy sources throughout production are the transfer of heat through the wall adjacent to the warm air storage (797 MJ) and periodic chamber ventilation with air from this storage (751 MJ). The sources of loss are the processes associated with the evaporation of moisture (235 MJ) and heat transfer through the front wall (97 MJ). Consequently, the gas phase, vital for maintaining chamber temperature, is an endoenergetic phase during both the soaking and growth stages. In the liquid phase, during the soaking stage, the energy source is external hot water supply (951 MJ), which means that this entire stage can be described as the endoenergetic part of the production process. However, during the growth stage, the energy emitted by the plant mass is absorbed by the cool water introduced into the chamber. The total heat generated by the growing sprouts and carried away from the biological mass during watering amounts to a substantial 4942 MJ. Thus, the liquid phase during the growth stage is exoenergetic, and the germinating plants can be viewed as an internal heat source within the chamber. Taking both the gas and liquid phases into account over the entire production cycle, the total net energy generated by the process is 3368 MJ. Figure 4 shows a summary of the shares of heat exchanged in the gas and liquid phases during the entire crop cycle in the growth chamber.

The total exergy losses throughout the entire sprout production process amount to 5.19 GJ. The largest losses are generated by the watering process, accounting for as much as 4.8 GJ. Conversely, other chamber processes, including water mixing (271 MJ, constituting 5.27% of losses) and water cooling down (2.71 kW) during seed soaking, chamber ventilation (33.3 MJ), and heat transfer through walls (ceiling - 22.7 MJ, front wall - 1.98 MJ), collectively contribute to only 6.5% of the total exergy losses. Notably, all exergy transport processes exhibit high exergetic efficiency, exceeding 70%. The organization of the mung bean sprout cultivation process ensures that a relatively small amount of exergy remains in each analyzed transport mechanism, which can potentially be converted into useful work. To summarize, it is evident that the biological processes occurring during Mung bean sprout cultivation serve as a substantial source of low-temperature waste heat with low exergy, offering potential for further utilization. The most optimal approach is to manage this heat at its point of generation, within the plant growing facility. This strategy can effectively reduce the energy demands of the production process, particularly in terms of the consumption of non-renewable fuels required for heating water used in crop watering phases.

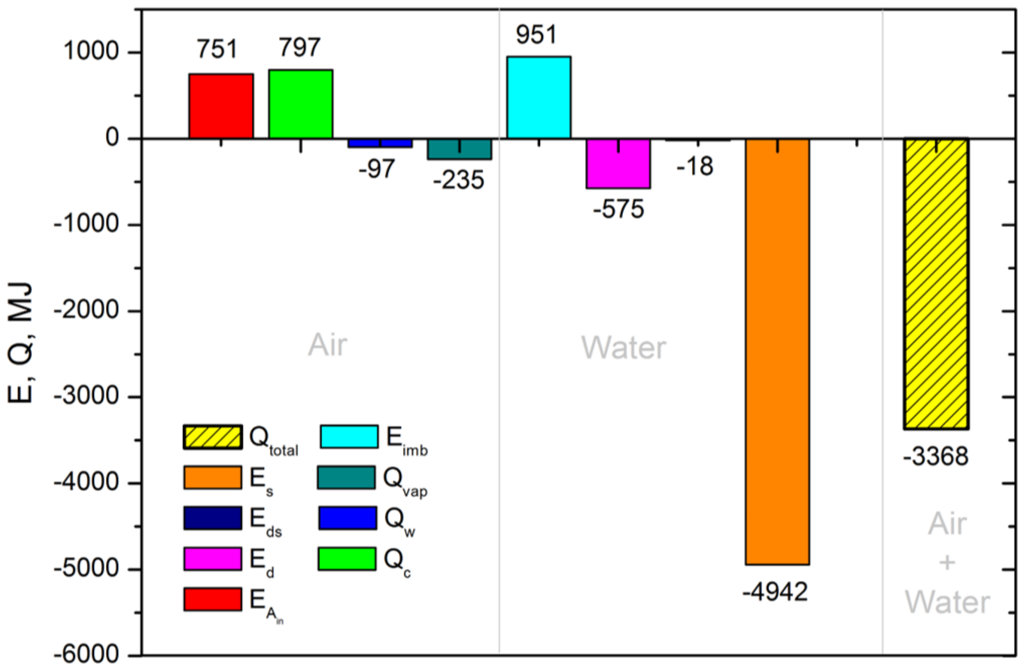

Figure 4 Summary of the heat exchanged in the gas and liquid phases during the entire plant growth cycle in the growth chamber (Q_{total}- total net heat generated by the sprouts , E_s- energy removed from the system, E_{ds} - energy contained in the irrigation water, which is discharged through a leak to the drain collector, E_d - energy contained in the imbibition water, which is discharged through a leak to the drain collector, $E_{A_{in}}$ - energy transferred in the gas phase by convective mixing, E_{imb} - energy supplied to the growth chamber during the imbibition phase, Q_{vap} - heat needed to evaporate the moisture, Q_w - heat exchanged in the gas phase by heat transmission through the front wall of the chamber, Q_c - heat coming from the heat storage through the heat transmission)

RESULTS OF SIMULATION RESEARCH

The total amount of energy transferred to fresh water in the two-stage waste heat recovery system for the complete production cycle of sprouts is approximately 22.18 GJ, as depicted in Figure 5. This value represents the heat requirement of the installation for the sprout production cycle. Of the total energy transferred, about 17.87 GJ is transferred on the HE1 heat exchanger, and the remaining 4.31 GJ on the second heating stage. Notably, the heat transferred to the fresh water in the first heating stage constitutes 80.6% of the total heat transferred. Furthermore, it is important to mention that all the heat transferred in the HE2 exchanger to the fresh water is partly composed of the electricity utilized to operate the compressor heat pump. Assuming an average COP of 7.5 for the heat pump, according to the actual data, the amount of heat recovered from the dirty water at the second heating stage is approximately 3.73 GJ.

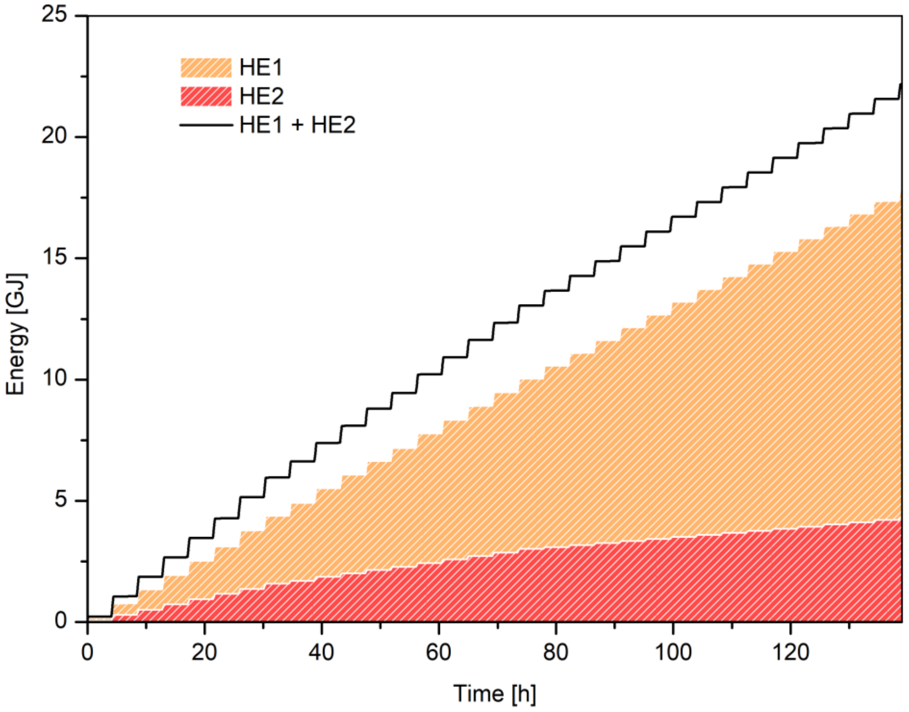

Figure 5 Total amount of energy transferred to fresh water in heat exchanger HE1 (1st stage of heating) and HE2 (2nd stage of heating).

The proposed energy recovery system effectively utilizes all the waste heat generated during the growth of sprouts and stored in the water after watering the biological mass. When considering the required energy to heat the fresh water (22.18 GJ) and the actual recoverable energy from sprout production (measured at 4.942 GJ), it becomes evident that relying solely on waste heat is insufficient to heat water for plant watering. Thus, alternative heat sources, such as an oil boiler, are necessary. Nevertheless, the proposed heat recovery system considerably decreases the energy consumption of the vegetable sprout plant, resulting in a reduction of approximately 1 ton of coal and avoiding emissions of around 6.1 Mg of CO_2 per week assuming operation at the nominal capacity of the production line (for one growth chamber, 198 kg and 1.24 Mg of CO_2 respectively).

CONCLUSIONS

Based on the conducted research and simulations, the following conclusions emerge:

1. The total heat generated by mung bean sprouts under laboratory conditions, with conditions mapped to the processing line, falls within the range of 1712 to 3157 J/g. This range represents the possible potential for heat recovery. The actual potential, determined through a balance analysis based on measurements taken on the production line, stands at 2287.4 J/g. For a single production cycle, this translates to a substantial 4942 MJ of recoverable heat. **Thus, the biological processes involved in cultivating vegetable sprouts can serve as a notable source of low-temperature waste heat**.
2. The use of a two-stage heat recovery system allows for the utilization of all available waste energy, resulting in an approximately 22.5% enhancement in the energy efficiency of the process for preparing water used in irrigating vegetable sprouts. Consequently, during the typical weekly operation of the entire facility, real savings in primary fuel consumption amount to nearly 1 ton of coal, leading to a reduction of approximately 6.1 Mg in carbon dioxide emissions. **This approach effectively reduces the energy intensity and reliance on conventional fuels in the plant dedicated to producing vegetable sprouts for consumption by harnessing waste heat generated by the plants**.
3. The developed laboratory measurement method for determining the total heat generated during the growth of mung bean sprouts, utilizing conditions similar to industrial-scale cultivation in an isothermal microcalorimeter, enables the assessment of the exploitable energy potential of these plants. This holds significant value as it facilitates the optimal selection of process parameters for plant cultivation, a task that was previously laborious and expensive due to reliance on trial-and-error methods.

Based on a literature review, the energy generated by vegetable sprouts has not been previously considered as a potential heat source. Nonetheless, the studies and simulations conducted in this research reveal that the *Vigna radiata* species produces a substantial amount of energy. Utilizing this energy on-site offers a significant enhancement in the energy efficiency of the production process. Upon analyzing the possible and actual energy potential values of the examined plants, while considering insights gleaned from exergetic analysis, it becomes apparent that managing the additional heat produced by the plants is achievable through alterations in the organization of sprout production. This type of analysis opens up a whole new area of future research focused on simulating the production process to identify the most efficient method for recovering heat from germinating mung bean seeds.