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KITCHEN AND GARDEN WASTE AS A SOURCE OF HEAT FOR GREENHOUSES

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ABSTRACT

The process of composting biological waste is a natural process – in which heat is released. Biological wastes generated in typical households in Poland – are mainly kitchen waste (KW) and green waste from home gardens (GGW – if they are owned). From the ecological point of view – the most advantageous method of their management is their utilization in the place of production. The paper presents a proposal for effective management of bio-waste arising by composting – with the simultaneous use of heat for greenhouse heating in autumn. This is to encourage residents to independently compost bio-waste – and increase the level of recycling of waste generated in Poland by 2020. Calculations for greenhouses were made – in accordance with the energy audit methodology. The obtained thermal balance results were compared with the actual temperature prevailing in the greenhouse in autumn. These calculations were the basis for calculating the amount of KW and GGW enabling effective heating of greenhouses in the autumn so that the internal temperature does not drop below 10ºC. It has been calculated that 22 kg of composted bio-waste (KW and GGW) will suffice to heat the greenhouse in October with an area of 18 m^2.

Introduction

Economic development and higher living standards lead to increased waste generation in households. In the United States, annual waste production is estimated at 839.5 kg per capita (*Hoornweg and Bhada-Tata, 2012*). By comparison, the relevant parameter was determined at 504 kg in the European Union (Kostecka et al, 2014) and 303 kg in Poland (GUS, 2017). Growing levels of environmental pollution, landfill overflow and the shortage of new landfill space have prompted many developed countries to introduce strict policies for sorting and recycling household waste (Edjabou et al, 2015; den Boer et al, 2010; Sahimaa et al. 2015). Municipal solid waste (MSW) combines various types of waste, a large proportion of which can be recovered and recycled (Arafat et al. 2015; Pandey et al., 2016). In line with the European Union's targets, 50% of waste should be re-used or recycled by 2020 in Poland (Łazarczyk and Gurgul, 2017).

Despite the above, waste recycling efficiency continues to be very low (Kuboń, 2008; Suthar and Singh, 2015). The above can be largely attributed to the lack of awareness that landfilled waste has a harmful impact on the environment as well as the absence of personal incentives for recycling. According to many studies (Zaman, 2015; Hottle et al, 2015, Cole et al., 2014). The goal of the zero waste philosophy is to prevent any waste from reaching landfills or incineration plants, since waste transport is also a source of environmental pollution. (Tan et al., 2015; Talaiekhozani et al., 2016; Wang et al., 2016) calculated the reduction in CO_2 emissions resulting from implementation of various waste sorting strategies. According to (Tatàno et al., 2015), the processing/recycling of biological waste at the site of generation is the optimal solution. Biological waste generated by households includes green garden waste (GGW). Garden waste is also frequently transported outside the household. Green waste can be effectively recycled by households to reduce the waste stream which reaches landfills (Neugebauer, 2017). Biological waste can be managed by composting. Composting is a natural process which takes place in several stages and generates heat. Under favorable conditions, the temperature inside the compost pile can reach 70-80ºC in the thermophilic phase (Pagans et al., 2006). The optimal temperature during the thermophilic phase is 55-60ºC. Composting temperature is influenced mainly by (Neugebauer and Sołowiej, 2014) aeration and the C/N ratio of the composted waste. The thermophilic phase generates substantial amounts of heat which can be reused. The recovery of heat from composted waste has been studied (Chambers, 2009), but the proposed solutions have not yet been deployed in practice (Walther et al., 2017). Composting, in particular if conducted under natural (field) conditions, is a relatively slow process, and the generated stream of heat has low density (Smith et al., 2016). The energy efficiency of composting is substantially reduced, sometimes even below the profit margin, if additional sources of energy or other resources (labor or materials) are required (Domitrz, 2016). For composting heat to be utilized effectively, the composting process should take place at the highest possible temperature without the involvement of external energy carriers.

The present study was conducted in a GGH (GGH) for the following reasons:

1. GGH and hotbeds are popular in residential gardens,
2. The proposed solution could be attractive for many households if the temperature inside a greenhouse supplied with compost-generated heat could increase to a level that prolongs the growing season and supports the production of crops longer in the fall or earlier in the spring. The proposed solution could popularize the collection and composting of kitchen and garden waste, thus reducing the stream of landfilled household waste and improving the overall energy balance of waste management. Composted organic matter is transformed into humus which constitutes excellent natural fertilizer.

Research hypothesis, objective and stages

In north-east Poland, heat generated during the composting process can be effectively recovered to heat residential GGH's in fall and spring.

The objective of this study was to design a GGH heating system supplied with heat from biological household waste, including kitchen waste (KW) and green garden waste (GGW), without the involvement of external energy carriers.

Research stages:
- The analysis was conducted in a GGH located in north-eastern Poland,
- Heat losses and heat gains in the analyzed GGH were calculated in the fall,
- The heat balance of the analyzed GGH was calculated,
- The temperature inside the GGH was modeled with the use of differential equations (at hourly intervals) and compared with the actual temperature measured inside the garden greenhouse. A thermal model of the GGH was developed and verified,
- The thermal model was used to calculate the amount of heat necessary to raise and maintain GGH temperature at a level suitable for growing crops in selected months of the year in north-eastern Poland,
- The quantity of biological waste required for composting and heating the analyzed GGH was calculated.

Calculations

The heat balance was calculated for the GGH presented in Figure 1. The GGH had an aluminum frame with 5 mm-thick polycarbonate panels. The cultivated area of the GGH is 13.5 m^2.

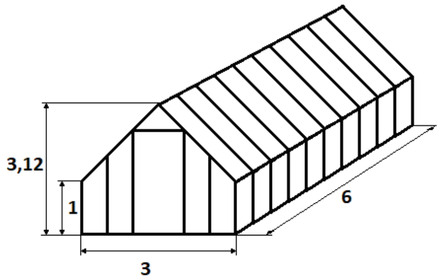

Figure 1. Diagram of the analyzed garden greenhouse. All dimensions are given in meters.

The thermal resistance R_T ($m^2 \cdot K \cdot W^{-1}$) of greenhouse walls (non-homogeneous partitions) (Standard PN 6946) was calculated with the use of equations (1-6). Thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$) was set at 0.21 for polycarbonate and 200 for aluminum (Standard PN 6946:1999).

$$R_T = (R'_T + R''_T) \tag{1}$$

$$1/R'_T = f_a/R_{Ta} + f_b/R_{Tb} \tag{2}$$

$$R_{Ta} = R_{Si} + R_a + R_{se} \tag{3}$$

$$R_{Tb} = R_{Si} + R_b + R_{se} \tag{4}$$

$$R''_T = R_{Si} + d/\lambda'' + R_{se} \tag{5}$$

$$\lambda''_3 = f_a \cdot \lambda_a + f_b \cdot \lambda_b \tag{6}$$

R_T – thermal resistance of a polycarbonate wall, ($m^2 \cdot K \cdot W^{-1}$)
R'_T – upper limit of total thermal resistance, ($m^2 \cdot K \cdot W^{-1}$)
R''_T – lower limit of total thermal resistance, ($m^2 \cdot K \cdot W^{-1}$)
R_{si} – thermal resistance on internal surface, ($m^2 \cdot K \cdot W^{-1}$)
R_{se} – thermal resistance on external surface, ($m^2 \cdot K \cdot W^{-1}$)
d – layer thickness, (m)
λ – thermal conductivity, ($W \cdot m^{-1} \cdot K^{-1}$)

The values of R_{si} and R_{se} were according to Standard PN 6946 – table 1.

Table 1.
Thermal resistance on surface

Thermal resistance ($m^2 \cdot K \cdot W^{-1}$)	The direction of the heat flow		
	up	horizontal	down
R_{si}	0.10	0.13	0.17
R_{se}	0.04	0.04	0.04

(Standard PN 6946:1999)

Total thermal resistance R_T of a non-homogeneous partition calculated from equation (1) was 0.1815 ($m^2 \cdot K \cdot W^{-1}$) for horizontal heat flow and 0.1515 ($m^2 \cdot K \cdot W^{-1}$) for vertical heat flow. Thermal transmittance (U-value) was calculated with the use of equation (7) according to Standard PN 6946:

$$U = \frac{1}{R_T}\ (W \cdot m^{-2} \cdot K^{-1}) \tag{7}$$

Thermal transmittance (U-value) was determined at 5.51 ($W \cdot K^{-1} \cdot m^{-2}$) for a vertical wall and at 6.60 ($W \cdot K^{-1} \cdot m^{-2}$) for the roof. The calculated ratio for the ratio of polycarbonate surface to the area occupied by aluminum elements in the GGH is 6.56. Heat loss to the ground was calculated according to Standard PN 12831:2003 (Table 2). The value of B' (m) (characteristic parameter, PN 12831) for the GGH presented in Figure 1 was determined at 2. It is the ratio of the floor area to the 1/2 of the perimeter of the floor. Therefore, U_{eq} = 1.3 ($W \cdot m^{-2} \cdot K^{-1}$) (Table 2, according to table 4 from PN EN 12831:2003).

Table 2.
U_{eq} -value of the floor

The value of B'	U_{eq} (for lowering the flor = 0 m, the flor on the ground) ($W \cdot m^{-2} \cdot K^{-1}$)				
	without insulation	U_{floor} = 2.0 $W \cdot m^{-2} \cdot K^{-1}$	U_{floor} = 1.0 $W \cdot m^{-2} \cdot K^{-1}$	U_{floor} = 0.5 $W \cdot m^{-2} \cdot K^{-1}$	U_{floor} = 0.25 $W \cdot m^{-2} \cdot K^{-1}$
2	1.30	0.77	0.55	0.33	0.17
4	0.88	0.59	0.45	0.30	0.17

(according to table 4 from PN EN 12831:2003 – fragments)

Heat loss resulting from heat transmittance H_{tr} in the GGH was calculated from equation (8). The calculated amount of heat loss is the sum of: heat loss through individual surfaces of side walls (product of individual surfaces times heat conduction and coefficient for GGH walls), sum of linear thermal bridges and heat losses through the floor on the ground – according to the PN 12831.

$$H_{tr} = \sum_k A_k \cdot U_k + \sum_l \Psi_l \cdot l_l + A_p \cdot U_{eq}\ (W \cdot K^{-1}) \tag{8}$$

A_k – surface area of component, k (m^2)
U_k – thermal transmittance of component, k ($W \cdot m^{-2} \cdot K^{-1}$)
l_l – length of thermal bridge, l (m)
Ψ_l – thermal transmittance of a linear thermal bridge, ($W \cdot m^{-1} \cdot K^{-1}$)
U_{eq} – thermal transmittance of dirt floor, ($W \cdot m^{-2} \cdot K^{-1}$)
A_p – surface area of dirt floor, (m^2)

Three thermal bridges were identified in the GGH in accordance with Standard PN 14683: thermal bridge GF4 between the wall and the dirt floor, bridge C4 in the corner, and bridge W10 by the door. Thermal bridges were calculated based on external dimensions according to Standard PN 14683. Thermal transmittance Ψ_e was determined at 0.50 ($W \cdot m^{-1} \cdot K^{-1}$) for bridge GF4, -0.15 ($W \cdot m^{-1} \cdot K^{-1}$) for bridge C4, and 0.10 ($W \cdot m^{-1} \cdot K^{-1}$) for bridge W10. The linear dimensions of thermal bridges were calculated based on figure 1.

The whole surface area of GGH walls was calculated based on figure 1. Heat transmittance H_{tr} was determined according to the formula 8 (for the whole GGH, that is, all heat losses, i.e., through side walls and roofs, by linear thermal bridges and through the ground):

$$H_{tr} = 301.5\ (W/K)$$

Projected heat loss Φ (W) was calculated according to Standard PN 12831 from equation (9):

$$\Phi = H_{tr} \cdot (t_i - t_e)\ (W) \tag{9}$$

t_i – temperature inside the GGH, (K)
t_k – temperature of ambient air, (K)

The temperature inside and outside the GGH was measured with DS18b20 sensors at hourly intervals. Heat loss over time was calculated as the product of Φ and time.

Solar gain was included in the heat balance of the analyzed garden greenhouse. Solar irradiance was measured with the Kipp&Zonnen model CMP3 pyranometer at hourly intervals.

Solar heat gain was calculated based on hourly solar irradiance ($W \cdot m^{-2}$) from equation (10) according to standard energy audit methodology:

$$Q_{SOL} = \Sigma_i\ (A_i \cdot I \cdot g \cdot k_a \cdot 1)\ (W \cdot h) \tag{10}$$

Q_{SOL} – solar gain, ($W \cdot h$)
i – cardinal directions (N, S, E, W) of solar radiation incident on the garden greenhouse
A_i – transparent area of GGH walls in a given direction, (m^2)
I – solar irradiance ($W \cdot m^{-2}$), based on pyranometer readings – measured outside the GGH

g – solar penetration across a transparent polycarbonate panel = 0.84 (according to Shepherd and Shepherd, 2014)
k_a – correction factor for I_i to account for the angle of the roof surface above the horizontal plane, according to Table 8 (Rozporządzenie, 2015)
1 – hour, (h)

The developed model was verified on two dates in fall, 1 October 2016 and 31 October 2016, by comparing the temperature measured inside the GGH with the modeled temperature. The calculations were made for GGH without plants. Formula (11) presents the heat balance equation, which is the basis for calculation of the temperature inside GGH. The temperature inside the GGH was calculated in view of heat loss to the ambient environment (based on the measured external temperature) and solar gain (based on the calculated solar irradiance and heat accumulation inside the garden greenhouse). The specific heat of humid air was calculated based on normalized values (Kurpaska, 2007).

$$Q_{h+1} = Q_h + Q_{SOLh} + Q_{COMh} - \phi_h \cdot 1hour\ (Wh) \tag{11}$$

Q_{h+1} – heat in next houer, (W·h)
Q_h – heat in the previous hour, (W·h)
Q_{SOLh} – heat in the previous hour from the sun, (W·h)
Q_{COMh} – heat in the previous hour from the compost heap, (W·h)
Φ_h – heat loss in the previous hour, (W·h)

The input data for the model made were the values (in individual hours of the day): indoor and outdoor temperature GGH, solar radiation, calculated design heat loss from GGH and on the next step the amount of heat generated and transferred to the air in GGH from the compost pile.

The temperature measured outside and inside the GGH on the two analytical dates and the corresponding modeled temperatures are presented in figures 2 and 3.

The root mean square error (RMSE) of modeled data was calculated for both analytical dates with the use of equation (11):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(t_{i\,rz} - t_{i\,mod})^2}{n}} \tag{11}$$

$t_{i\,rz}$ – temperature measured inside the garden greenhouse
$t_{i\,mod}$ – modeled temperature inside the garden greenhouse
n – number of measurements (sample size)

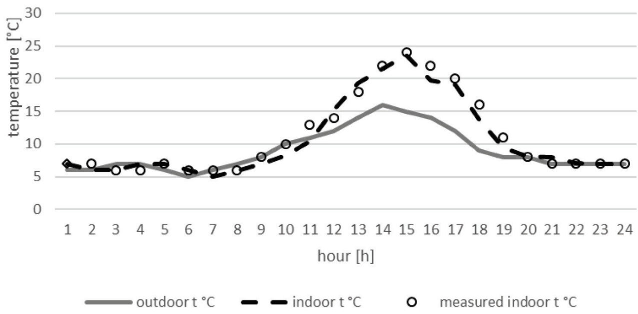

Figure 2. Changes in temperature on 1 October 2016. The value of RMSE between the measured and calculated indoor temperature is 2.07

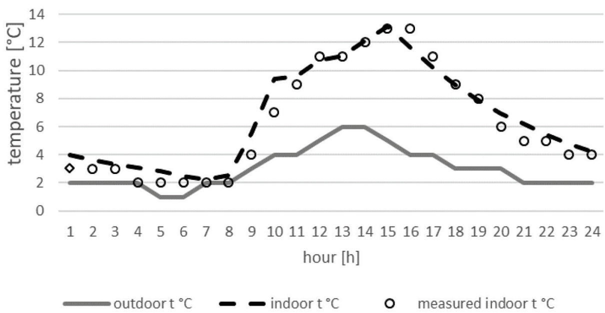

Figure 3. Changes in temperature on 31 October 2016. The value of RMSE between the measured and calculated indoor temperature is 1.69

The value of RMSE indicates that the developed model effectively predicted the measured temperatures. The standard deviation of the modeled values did not exceed two degrees for 1 October 2016 and was lower for 31 October 2016.

Calculating the quantity of compost for GGH heating in the fall

The temperature model was not developed to predict temperatures inside the GGH, but to determine the quantity of compost required to heat the GGH and maintain indoor temperature at minimum 10ºC in the fall.

The quantity of compost was calculated based on the following assumptions:

The composted biological waste is generated in households and residential gardens. Biological household waste can be utilized as a source of energy. Household waste is a less efficient source of heat than manure, but it is readily available in every household. Kitchen waste and GGW are combined in equal proportions (1:1 by weight). According to the literature, up to 12 MJ of heat can be recovered from 1 kg of compost (Jędrczak, 2008). The cited value represents the maximum heat output under optimal composting conditions, including the optimal C:N ratio and optimal aeration, and it can be lower in real-life conditions. Neugebauer (2018) recovered 1.41 MJ of heat from 1 kg of compost, but the cited author measured only the heat generated inside the evaluated facility without heat loss to the ambient environment which also takes place during composting. In the present study, the potential heat recovery from 1 kg of compost was set at 6 MJ – considering the heat transfer efficiency from compost to the aeration air of the prism (in accordance with the idea contained in the described patent).

Compost piles were situated inside the greenhouse, and the generated heat was transmitted in its entirety to the air inside the garden greenhouse. A passive aeration system based on a patented solution was used (Neugebauer, 2017). The idea of a patent lies in the fact that the heat from the compost is immediately released into the surrounding air. This kind of a passive aeration system eliminates the need for external energy sources, which is consistent with the preliminary assumptions. According to the developed model, around 21,6 kg of compost would be required to heat the greenhouse in October. The heat generated by compost was taken into account in the model. According to calculations, the temperature inside the GGH could be maintained at minimum 10ºC (fig. 4) if 4.32 MJ of energy were generated daily (data modeled for 31 October 2016), which is consistent with the research assumptions.

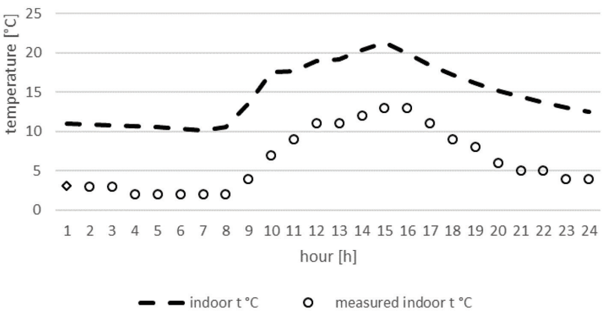

Figure 4. The modeled changes in the temperature of the GGH supplied with compost heat on 31 October 2016

Conclusions

The energy balance of a GGH was simulated with the use of a model predicting temperatures inside the garden greenhouse. The model was developed with the involvement of differential equations at hourly intervals. The actual temperatures measured inside the GGH and the modeled temperatures were compared. The calculations were made only for October in order to show the correctness of the model. This month was chosen deliberately. It is too cold in GGH to cultivate plants in GGH in north-eastern Poland and, after re-heating, the growing season can be extended. Measurement data from other months of the year are currently being processed, in subsequent articles, analyzes for other months will be made.

The developed model was used to determine the quantity of compost required for heating the greenhouse in October and for maintaining the temperature inside the GGH at minimum 10ºC. According to the calculations, 22 kg of compost would be required to heat the GGH in the analyzed month.

Similar simulations can be performed for other months, such as November and March. The presented model was developed for kitchen waste and green garden waste combined in equal proportions. The described solution can be easily implemented to residential gardens.

The proposed system also increases CO_2 concentration inside the garden greenhouse, which promotes the growth of crops. Composted waste is transformed into humus which constitutes highly suitable fertilizer for gardening (Neugebauer and Sołowiej, 2017).

The described solution could encourage households to manage biological waste in residential gardens, thus decreasing the stream of landfilled waste and contributing to a global reduction in CO_2 levels.

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BIOODPADY KUCHENNE I OGRODOWE JAKO ŹRÓDŁO CIEPŁA DO OGRZEWANIA SZKLARNI

Streszczenie. Proces kompostowania odpadów biologicznych jest procesem naturalnym – w którym wydzielane jest ciepło. Odpady biologiczne powstające w typowych gospodarstwach domowych w Polsce – to przede wszystkim odpady kuchenne (Kitchen Waste) i odpady zielone z przydomowych ogródków (GGW – w przypadku ich posiadania). Z punktu widzenia ekologicznego – najkorzystniejszą metodą ich zagospodarowania jest ich utylizacja w miejscu powstawania. W pracy pokazano propozycję efektywnego zagospodarowania powstających bioodpadów poprzez ich kompostowanie – z jednoczesnym wykorzystaniem ciepła do ogrzewania szklarni jesienią. Ma to zachęcić mieszkańców do samodzielnego kompostowania bioodpadów – i zwiększyć wymagany do 2020 roku poziom recyklingu powstających w Polsce odpadów. Wykonano obliczenia dla szklarni – zgodnie z metodyką audytu energetycznego. Uzyskane wyniki bilansu cieplnego porównano z rzeczywistymi temperaturami panującymi w szklarni jesienią. Obliczenia te były podstawą do obliczenia ilości KW i GGW umożliwiającej efektywne dogrzanie szklarni jesienią tak – aby temperatura wewnątrz nie spadła poniżej 10ºC. Wyliczono, że 22 kg kompostowanych bioodpadów (KW i GGW) wystarczą do dogrzania szklarni w październiku o powierzchni 18 m^2.

Słowa kluczowe: kompostowanie, odbiór ciepła, szklarnia, ogrzewanie