Thermoeconomic Analysis of Reducing Exergy Losses in Greenhouses with Hydroponic Cultivation System through Drainage Recycling and Formation of Water Quality Pyramid

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Extended Abstract

Introduction: Agriculture is the largest consumer of water in the world, and employing non-conventional water resources along with treatment and recycling is considered the main resource in addressing future water scarcity. In a process, by dissolving different materials at different costs in water, different solutions are made, each of which has its own application to achieve the goal of the system. Eventually, water flows out of the system as sewage after passing through various technologies. Recycling makes it possible to convert low quality water (wastewater) into high quality water (Fresh water).

As reviewed, LCA, ELCA, water flow exergy analysis, physical hydronomic, and exergy cost analysis are among the methods used in previous research to express the recycling effect and reflect water quality. However, in order to achieve a comprehensive analysis of the recycling system, there are some shortcomings in the mentioned methods as following:

- Lack of reflection of flow quality in analysis (LCA defect)
- Lack of comprehensiveness of water quality indicators, such as BOD, TOC, TDS, and so on, to compare all water flows in the system. Although these indicators indicate the differentiation of flows in terms of standards related to the dimensions of one of the mentioned criteria, they do not provide the possibility of comparing different flows considering the system goal (sustainable production) as well as classifying flows in different sectors (the shortcoming of water environmental indicators)
- Impossibility of reflecting the cost consumed for the flow and, therefore, the impossibility of providing differentiation of several water flows in different parts of the system (the shortcoming of exergy analysis)
- Failure to consider the role of technology and the flow of capital expenditure for it (the shortcoming of exergy cost analysis)
- Impossibility of monetizing methods to facilitate decision-making for use in policy-making

Previous studies have not investigated exergy losses and exergy destruction in the analysis of fertigation recycling system and comprehensive exergoeconomic analysis on fertigation system. Besides, they have not compared the results for both open and close systems (recycling system). Due to the shortcomings mentioned in the previous works, the present study has employed the thermo-economic method to integrate the cost of resource consumption with other economic cost items and finally, to express the distribution of exergoeconomic cost accumulation of flows in the system and monetize the results. Finally, for the first time, the distinction between different systems of water flow and their classification, based on exergoeconomic cost accumulation, has been presented in the form of a water quality pyramid.

Materials and Methods: In this case study, exergoeconomic cost, through using a hydroponic greenhouse system for rose cultivation, was investigated in a recycling process by comparing three scenarios including an open cycle, an open cycle considering exergy abatement cost, and a close cycle (nutrition water recycling).

The conceptual model of the case study has been elaborated. After describing the methodology including the equations of exergy analysis and thermoeconomic analysis, the exergoeconomic cost of production from recycling in a comprised format of open, open cycle considering exergy abatement cost, and close hydroponic irrigation cycle is presented. In fact, this is one of the innovations the present research has contributed to current literature.

Next, the water quality pyramid for classification and differentiation of water flows in the greenhouse system, based on the unit exergoeconomic cost index is formed, which is one of the most important achievements of the present study.

Result: Results show that the exergoeconomic cost for producing 212,500 rose cut-flowers in a 6-monthcold period, when heat was supplied by boiler for the above mentioned scenarios were about $15760, $16,525 and $14,718 respectively. Also, the thermoeconomic indicators of the unit exercoeconomic costs were 74.2, 77.8 and 69.3 $.Gj-1 respectively. In the close cycle, the drainage of water recycling decreased total exergy losses by 4.02 $Gj.y^{-1}$, of which a reduction of 1.24 $Gj.y^{-1}$ was due to the reduced inlet water and 1.91 $Gj.y^{-1}$ for the inlet fertilizer reduction, while an increase of 1.12 $Gj.y^{-1}$ occurred by the electricity consumption of the system. The presented water quality pyramid, based on the unit exergoeconomic cost, indicated 459.9 $Gj.y^{-1}$ as the highest peak value for the nutrition feed and zero for the wastewater at the base of the pyramid.

Discussion: The results of present study have shown that exergoeconomic cost of production in a close cycle is lower than an open cycle. In other cases in the prvious studies, it was noted that the exergoeconomic cost of generating electricity by a close cycle is less than an open state. As a result, the indicator of decrease total exergoeconomic cost of production could show the rationality of the chosen recycling process for the system.
On following the value of index c, according to the ratio of the cost spent to the amount of exergy of each flow, is an indicator that is not dependent on the mass of flow and shows the differentiation of water flow. As a result, the water flow quality pyramid in the greenhouse system, based on the unit exergoeconomic cost index (c), has been obtained as Fig. 1. The water quality pyramid, based on index c, is one of the achievements of thisstudy, which is presented for the first time for a greenhouse system. In the quality pyramid presented in Fig. 1, the classification of flows is presented based on the name of the flow generating technology along with the flow tag number in Fig. 1.

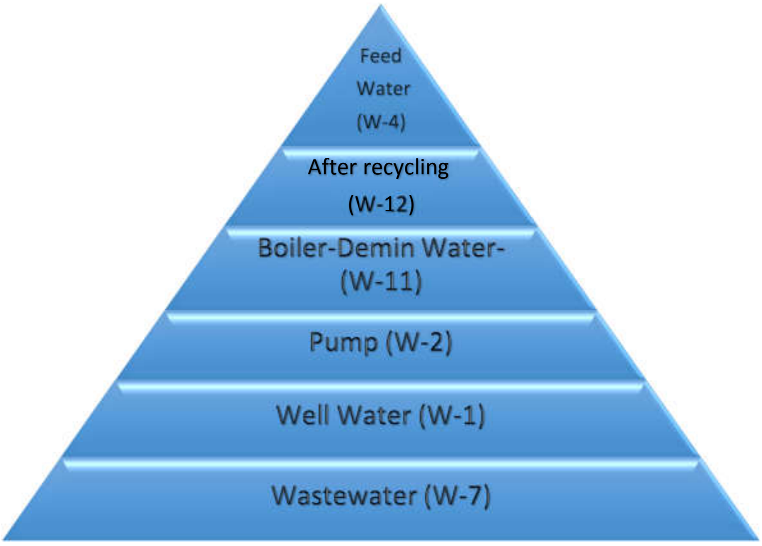

Fig. 1. Quality pyramid of water flows based on unit exergoeconomic cost

Conclusion: In the present study, exergoeconomic analysis of recycling system was performed for the case study of an open and a close fertigation system in the greenhouse for the first time. ΔExC in open and close cycles has been introduced as an indicator of selecting recycling technology from a thermoeconomic point of view. Using recycled flows is one of the most important solutions to reduce resource consumption.

The results of exergy and exergoeconomic analyses of an open, an open cycle considering exergy abatement cost, and the close system analysis of ΔExC showed that

- The exergy losses of the system are reduced with recycling. Recycling reduces the exergy destruction of some resources. Although the use of recycling technology is associated with exergy destruction, the positive sign of diverse exergoeconomic costs of open and close systems have been presented as indicators for the rationale of using recycling technology in the present study.

- Although water quality indicators such as pH, EC, and so on do not allow to differentiate between water in different parts of the system, the unit exergo-economic cost index, a criterion for classifying water flows in the system based on the exergoeconomic cost per exergy, is in line with the goal of the system. As a result, the water quality pyramid in the system can be formed to classify the types of flows based on the unit exergoeconomic cost.

Using exergoeconomic analysis of open and close cycles in the greenhouse system, the differences between rose production in open and close exergoeconomic cost were calculated. The unit exergoeconomic cost of rose production in a close cycle was 69.3 \$/Gj (6.93 ₡/Cut flower), 4.9 \$/Gj (0.49 ₡/Cut flower) less than the open cycle scenario. As a result, the difference of open and close exergoeconomic has a positive value, and the use of wastewater recycling in newly built Nikan Rose Greenhouse is thermoeconomically rational.

Finally, by calculating the unit exergoeconomic cost of flow for all types of water flows with different qualities, a water quality pyramid is formed that differentiates flow based on the accumulation cost spent to achieve the system goal. For the greenhouse, pilot studied in the present research, feed water with exergoeconomic cost equal to 501.8 $\$.Gj^{-1}$ for open cycle and 459.9 $\$.Gj^{-1}$ for close cycle had the highest value and are at the top of the pyramid. Sewage with zero value had the lowest value and was at the bottom of the pyramid. The rest of flows are ranked and listed between these two values. This achievement of the present study makes it possible to compare and evaluate flows in a system.

Keywords: Recycling, thermoeconomic analysis, greenhouse hydroponic cultivation, water quality pyramid, unit exergoeconomic cost.

References

[1] Panagopoulos. A., "*Water-energy nexus: desalination technologies and renewable energy sources*", Environmental Science and Pollution Research, Vol. 1, No. 14, 2021.

[2] Dubreuil, A., Assoumou, E., Bouckaert, S., Selosse, S. and Maı, N., "*Water modeling in an energy optimization framework–The water-scarce middle east context*", Applied energy, Vol. 101, pp. 268-279, 2013.

[3] Pokhrel, P., Lin, S-L. and Tsai, C-T., "*Environmental and economic performance analysis of recycling waste printed circuit boards using life cycle assessment*", Journal of Environmental Management, Vol. 276, pp. 111-276, 2020.

[4] Valero, A., Magdalena, R., Calvo, G., Ascaso, S., Círez, F. and Ortego, A., "*Eco-credit system to incentivise the recycling of waste electric and electronic equipment based on a thermodynamic approach*", International Journal of Exergy, Vol. 35, No. 1, pp 132-154, 2021.

[5] Wang, S., Dai, Y., Ma, Z., Qi, H., Chen, Z., Shen, Y., et al, "*Application of energy-saving hybrid distillation-pervaporation process for recycling organics from wastewater based on thermoeconomic and environmental analysis*", Journal of Cleaner Production, Vol. 294, pp. 126-297, 2021.

[6] Castro, MBG., Remmerswaal, JAM., Brezet, JC. and Reuter, MA., "*Exergy losses during recycling and the resource efficiency of product systems. Resour Conserv Recycl*", Vol. 52, pp. 219-233, 2007.

[7] Trubyanov, MM., Shablykin, DN., Mokhnachev, NA., Sergeeva, MS., Vorotyntsev, A V., Petukhov, AN., et al. "*A hybrid batch distillation/membrane process for high purification part 1: Energy efficiency and separation performance study for light impurities removal*", Separation and Purification Technology, Vol. 241, 2020.

[8] Wang, C., Jin, H., Peng, P. and Chen, J., "*Thermodynamics and LCA analysis of biomass supercritical water gasification system using external recycle of liquid residual*", Renewable Energy, Vol. 141, pp. 1117-1126, 2019.

[9] Amini, SH., Remmerswaal, JAM., Castro, MB. and Reuter, MA., "*Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis*", Journal of Cleaner Production, Vol. 15, No. 10, pp. 907-913, 2007.

[10] Seawright, KW., Young, ST., *"A quality definition continuum"*, Interfaces (Providence), Vol. 26, No. 3, pp. 107-113, 1996.

[11] Bartram, J. and Balance, R., "*Water quality monitoring - a practical guide to the design and implementation of freshwater*", Quality Studies and Monitoring Programmes, pp. 1-348, 1996.

[12] Ayers, RS., Westcot, DW., *"Water Quality for agriculture"*. FAO UNITED NATIONS, Rome, Italy, 1985.

[13] Ye, F. and Kameyama, S., "*Long-term spatiotemporal changes of 15 water-quality parameters in Japan: An exploratory analysis of countrywide data during 1982–2016*", Chemosphere, Vol. 242, pp. 125-245, 2020.

[14] ER Rene, MS., "*Prediction of water quality indices by regression analysis and artificial neural networks*", Vol. 2, No. 2, pp. 547-550, 2008.

[15] Carrasquer, B., Uche, J. and Martínez-Gracia, A., "*Exergy costs analysis of groundwater use and water transfers*", Energy Conversion and Management, Vol. 110, pp. 419-427, 2016.

[16] Hosseinnejad, A., Saboohi, Y. and Shayegan, J., "*WEMS-1: Watergy integrated modelling for optimal technology assessment in steel Industry- Case study: Esfahan Mobarakeh Steel Company (MSC)*", Scientific of Energy Engineering & Management, Vol.10, NO.1, PP, 54-71, 2020 (in persian).

[17] Stanek, W. and Stanek Editor, W., "*Thermodynamics for sustainable management of natural resources (green energy and technology)*", Springer; 2017.

[18] Huang, LQ., Chen, GQ., Zhang, Y., Chen, B. and Luan, SJ., "*Exergy as a unified measure of water quality*", Communications in Nonlinear Science and Numerical Simulation, Vol. 12, No. 5, pp. 663-672, 2007.

[19] Martínez, A. and Uche, J., "*Chemical exergy assessment of organic matter in a water flow*", Energy, Vol. 35, No. 1, pp. 77-84, 2010.

[20] Dincer, I. and Rosen, MA., "*Exergy: energy, environment and sustainable development*", Newnes, 2012.

[21] Javaherdeh, K., Naghashzadegan, M. and Saadatmand, Sh., "*Optimization and thermoeconomic analysis of solar lithium bromide-absorption chiller*", 19th Annual Conference on Mechanical Engineering, 2011, (in persian).

[22] Hanifi, K., Javaherdeh, K. andYari, M., "*Exergy and exergoeconomic analysis and optimiza tion of the cogeneration cycle under solar radiation dynamic model using genetic algorithm*", Exergy for A Better Environment and Improved Sustainability 1, Springer, pp. 1139–60, 2018.

[23] Carrasquer, B., Uche, J. aMartínez-Gracia, A., "*Exergy costs analysis of grnd oundwater use and water transfers*", Energy Conversion and Management, Vol. 110, pp. 419-427, 2016.

[24] Gai, L., Varbanov, PS., Van Fan, Y., Klemeš, JJ. and Romanenko, SV., "*Trade-offs between the recovery, exergy demand and economy in the recycling of multiple resources*", Resources, Conservation and Recycling, Vol. 167, 2021.

[25] Frangopoulos, C., "*Exergy, energy system analysis, and optimization, Volume II*", Encyclopedia of Life Support Systems, Vol. 2, 2009.

[26] Tsatsaronis, G. and Pisa, J., "*Energy Systems - Application To the Cgam Problem*", Energy, Vol. 19, No. 3, pp. 287-321, 1994.

[27] Di Fraia, S., Macaluso, A., Massarotti, N. and Vanoli, L., "*Geothermal energy for wastewater and sludge treatment: An exergoeconomic analysis*", Energy Conversion and Management, Vol. 224, pp. 113-180, 2020.

[28] Chitsaz, A., Hosseinpour, J. and Assadi, M., "*Effect of recycling on the thermodynamic and thermoeconomic performances of SOFC based on trigeneration systems: A comparative study*", Energy, Vol. 124, pp. 613-624, 2017.

[29] Conrad, K., "*A theory of production with waste and recycling*", Discussion papers/Institut für Volkswirtschaftslehre und Statistik; Department of Economics, Universität Mannheim, Vol. 550, 1997.

[30] Valero, A., Botero, E. and Valero, A., "*Global exergy accounting of natural resources*", Exergy, Energy System Analysis, and Optimization, 1st ed.; Frangopoulos, CA, Ed, pp. 409-420, 2009.

[31] Vox, G., Teitel, M., Pardossi, A., Minuto, A., Tinivella, F. and Schettini, E., "*Sustainable greenhouse systems*", Sustainable agriculture: technology, planning and management. Nova Science Publishers, Inc., New York, NY, USA, pp. 1-79, 2010.

[32] Mokhtari, M. and Rostami, M., "*Energy and exergy analysis of two configurations of organic rankine cycle in heat recovery of intenal combustion engine*", Iranian journal of mechanical engineering (ISME), Vol.4, 2021 (in persian).

[33] Saboohi, Y., "*Energy Supply Model: ESM*", Sharif Energy Research Institute (SERI), Technical Report, 2005.