Environmental impact of tomato production under different hydroponic systems

F.T. Tewolde[1], M. Takagaki[1,2], T. Oshio[2], T. Maruo[1,3], T. Kozai[3] and Y. Kikuchi[4]

[1]Graduate School of Horticulture, Chiba University, Matsudo, Japan; [2]Center for Environment, Health and Field Science, Chiba University, Kashiwa, Japan; [3]Japan Plant Factory Association, Kashiwa, Japan; [4]Organization for Interdisciplinary, Research Project, University of Tokyo, Tokyo, Japan.

Abstract

This study aimed to evaluate the environmental burden of three hydroponic tomato production systems using partial life cycle assessment (LCA). System-1 was modified nutrient film technique (NFT), in which the solution does not flow longitudinally but rather horizontally and it secures an even nutrient solution to each plant. System-2 was traditional NFT system in which the nutrient solution was recirculating the whole day continuously. System-3 was a tray that had 10 growing pots of 250 mL volume. These pots were filled with granulated rock wool and used a drip-irrigation system activated by a solar radiation threshold. All inputs and outputs of each hydroponic system were classified into structural materials, cultivation inputs and waste. The analysis shows that the environmental burden from cultivation was significantly higher for all three systems than the environmental burden from structural materials and waste. Among inputs considered under cultivation, the environmental burden from fertilizer was the highest as a result of production. However, use emissions were not considered as all systems were closed loops. System-2 had a high total environmental impact because of its considerably higher resource consumption compared to others. Water had significantly a lower environmental burden in all systems. However, all systems had different water consumptions and System-3 was the lowest for water consumption. The environmental burden from fertilizer could be minimized by a proper fertigation schedule and it needs to be examined in more detail and improved as it is the most visible environmental burden. An efficient irrigation schedule would also directly minimize the overall environmental burden due to its direct relation with all inputs used during cultivation.

Keywords: LCA, environmental impact, hydroponics, greenhouse tomato production

INTRODUCTION

The world population is increasing dramatically and this population increase means greater food demand, which is leading to an increase in protected food crop production. The area covered by protected agriculture systems (plastic mulch, plastic tunnels and greenhouses) has been expanding in response to year round demand by consumers for fresh agricultural food products (Torrellas et al., 2012; Khoshnevisan et al., 2014). The total area of greenhouses world-wide is estimated to be approximately half a million hectares (Antón et al., 2005). As the expansion of protected crop production industry continues, the agriculture has become one of the world's largest food industry sectors and a large consumer of natural resources. Studies in the food sector clearly demonstrate that it is one of the most prolific energy users and a significant contributor to global warming potential (GWP) (Beccali et al., 2009; Cooper et al, 2011).

It is thus essential to evaluate the environmental impact of resource utilization for sustainable food production and consumption. Many LCA studies have been done for different crops in different countries, including fresh tomato and tomato products. It has been reported on in relation to the method of cultivation; greenhouse or open field, organic or conventional, and hydroponic or soil-based and cultivar (Andersson et al., 1998; NIAES, 2003; Antón et al., 2005; Williams et al., 2006). Specific applications of LCA in greenhouses

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has been used to evaluate cultivation techniques: heating, artificial illumination, and carbon fertilization and crop nutrition: soilless, with substrate, and with substrate plus recirculation (Romero-Gámez et al., 2012). These studies vary widely on the emissions from cultivation in particular, perhaps because of differences in location, method of cultivation, and cultivar. It has also reported that GHG emissions from tomato cultivation in greenhouses are dependent on the type and construction of the greenhouse (Antón et al., 2005). In this study we evaluated and compared the environmental burden of tomato production under three different hydroponic systems used in a "plant factory" using partial life cycle assessment (LCA).

MATERIALS AND METHODS

Life cycle assessment (LCA) is a tool used to evaluate environmental load associated with a product, process, or service by identifying and quantifying energy and resource consumption as well as emissions and wastes released to the environment. Thereby, it provides opportunities for environmental improvement of any specific process stage that is identified and assessed. According to ISO 14040 (1997), LCA consists of four phases, which includes goal and scope definition, inventory analysis, impact assessment, and interpretation. These steps were followed in this study.

Goal and scope definition

The purpose of this study is to evaluate the environmental burden of tomato production under different hydroponic systems and to identify where a high environmental load is found in each system throughout the tomato production process and to compare the systems' resource-use efficiencies.

Different studies differ in their choice of system boundaries. In this study the structural materials (steel, HDPE, polystyrene, granule rock wool) used to make the hydroponic system, cultivation inputs (fertilizer used, water and electricity used for irrigation pump) and waste were considered. Materials that are used in all systems in common such as: greenhouse structure, covering materials, energy used for heating/cooling, and other are not considered because they are all used in same quantity and quality for all production systems and their incorporation into the analysis would not make any difference. The functional unit of this study was one hectare tomato production.

The three hydroponic systems were as follows. System-1 was a modified Nutrient Film Technique (NFT), and unlike other hydroponic systems, the nutrient solution does not flow longitudinally but rather horizontally and it was designed to secure an even distribution of the nutrient solution to each plants with 1 min of irrigation every 10 min schedule. The nutrient solution was supplied from a plastic water tube that has tiny holes from which nutrient solution flows onto an unwoven sheet where the root system was grown on (Figure 1A). System-2 was traditional Nutrient Film Technique (NFT) in which the nutrient solution flows from one end to the other end of the cultivation bed (Figure 1B). Unlike the other two systems nutrient solution was supplied to the root system continuously for 24 h day^{-1}. System-3 was a system that uses a tray which has 10 connected small pots of 250 mL volume. These pots were filled with granulated rock wool (particle type rock wool) as a growing medium (Figure 1C). In this system the small volume of the pot makes the plant to grow with a tight root system. However, the plants get the required amount of water scheduled based on solar radiation integral through drip irrigation. Drip irrigation was activated when cumulative solar radiation reached a value of 1 MJ m^{-2}.

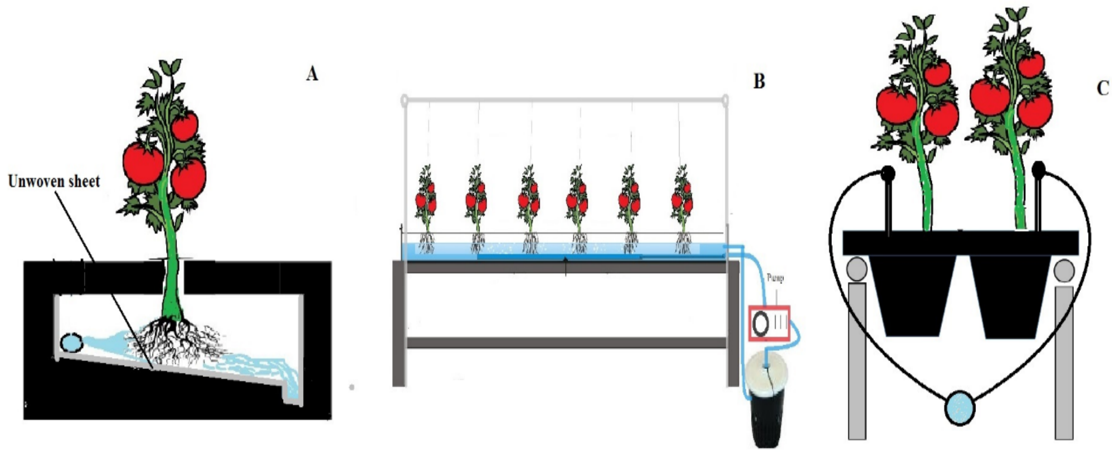

Figure 1. (A) Modified Nutrient Film Technique, (B) traditional Nutrient Film Technique in which nutrient solution flow from one end to the other end of the cultivation bed and (C) a tray which have 10 connected small pots of 250ml volume with drip irrigation activated when cumulative solar radiation reached a value of 1 MJ m^{-2}.

Inventory

During the life cycle inventory (LCI) stage, data collection and calculation techniques to quantify the relevant inputs-outputs of the systems were undertaken. The material used and emissions connected to these different input materials of hydroponic tomato production systems were compiled. In order to make an inventory of all inputs and outputs of a hydroponic tomato production system were categorized into three sub-systems: 1) structural (only hydroponic system), 2) cultivation and 3) waste.

Impact assessment

In this phase, impact categories were evaluated against inventory data. In order to facilitate the data handling and to make characterization and interpreting phases easier, the JEMAI's (Japan Environmental Management Associations for Industries) software MiLCA was used. The impact categories analysed were GWP (global warming potential), RC (resource consumption), AP (acidification potential), POCP (photochemical oxidation potential), EP (eutrophication potential), HT (human toxicity), (EC) energy consumption, and WC (water consumption) (Table 1). This process involves associating the inventory data with specific environmental impact categories and category indicators, in order to understand impacts.

Table 1. Results of the LCA for each hydroponic system.

Impact categories	Unit	System 1	System 2	System 3
Global warming	kg-CO_2 eq.	2.98E+04	3.87E+04	3.06E+04
Resource consumption	kg-Sb eq.	6.42E+01	5.87E+01	6.00E+01
Acidification	kg-SO_2 eq.	2.02E+01	2.39E+01	2.25E+01
Photochemical oxidation	kg-ethylene eq.	2.10E-01	3.93E-01	2.00E-01
Eutrophication	kg-phosphate eq.	1.14E-03	1.86E-03	1.10E-03
Human toxicity	kg-benzene air eq.	2.80E-03	4.29E-03	2.65E-03
Energy consumption	MJ	5.28E+05	7.05E+05	5.52E+05
Water consumption	kg	1.07E+07	1.27E+07	1.01E+07

RESULTS AND DISCUSSION

Based on the data collected from the experiment, the life cycle impact assessment results show that the environmental burden from cultivation was significantly higher for all three hydroponic systems (Figure 2A-C). Among the inputs considered during cultivation, the environmental burden from fertilizer was the highest (Figure 2D-F) in the production stage. However, use emissions were not considered as all systems were closed-loops. System-2 had high total environmental burdens because of its considerably higher input consumption (Table 1).

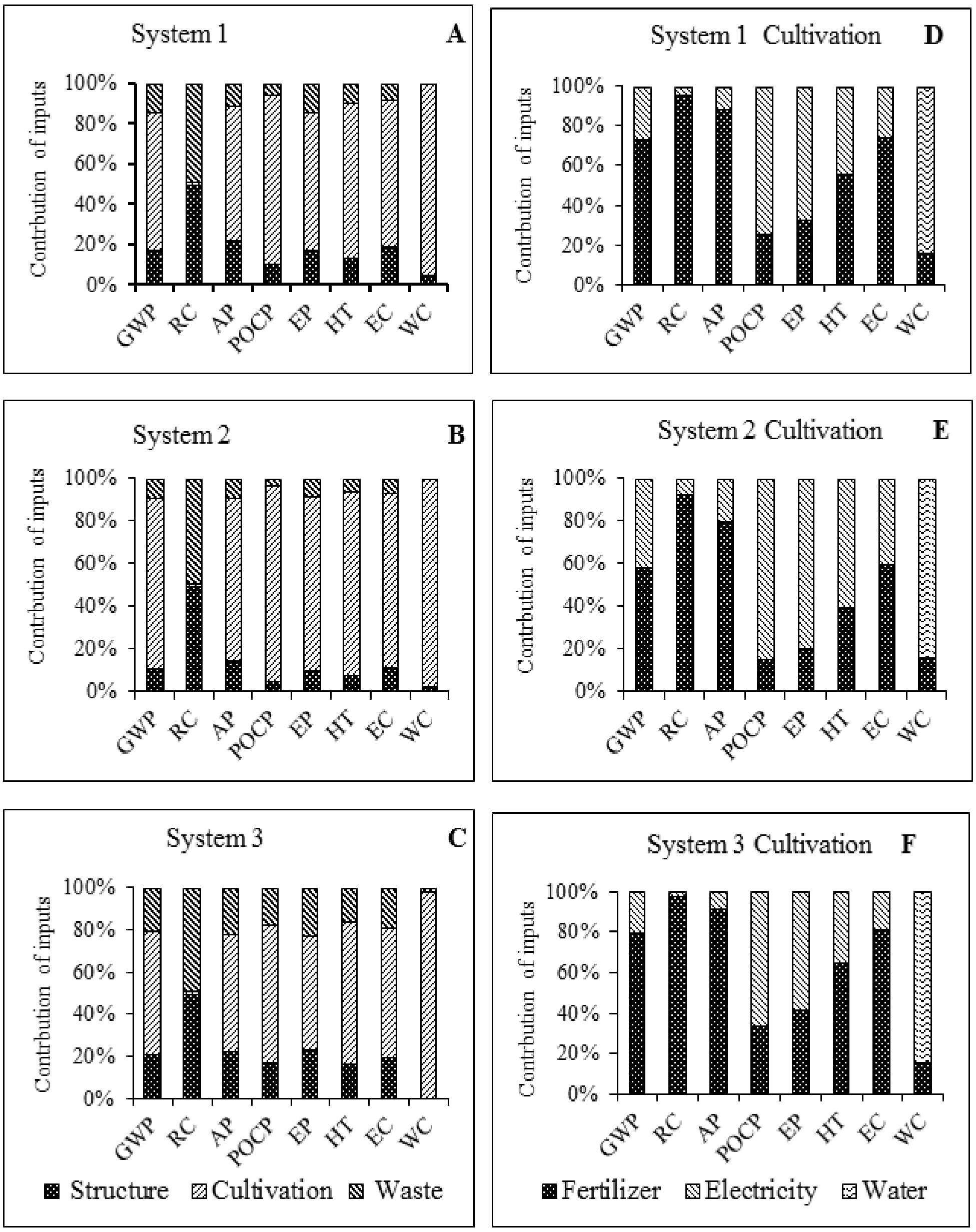

Figure 2. Results of the LCA for each hydroponic system; system 1 (A), system 2 (B) and system 3 (C) and a cultivation components of each systems system 1 (D), system 2 (E) and system 3 (F) with respect to impact categories; GWP (global warming potential), RC (resource consumption), AP (acidification potential), POCP (photochemical oxidation potential), EP (eutrophication potential), HT (human toxicity), (EC) energy consumption, and WC (water consumption).

Water had a significantly lower environmental burden across all systems. However, all systems had different water consumptions and System-3 recorded the lowest water consumption. This is because the system was designed to irrigate when it is necessary based on the solar radiation integral. The structures of the hydroponic systems also contributed significant amounts of burden on the environment. System-1 showed the highest environmental burden from structural materials, followed by System 2 and System 3, respectively.

For all the systems, the environmental burdens could be minimized by using a proper fertigation schedule and this needs to be examined in detail and improved. An efficient irrigation system will also directly minimize the overall environmental burden due to its direct relation with all inputs used during cultivation, such as fertilizer, water and the electrical energy used for irrigation pumping.

CONCLUSION

The choices made by growers in greenhouse hydroponic tomato production should consider both short and long term environmental consequences. An LCA methodology is currently the most dependable means available to make these choices as it provides a complete overview of the input-output flows of materials and the environmental consequences as a result of these choices. Our study highlights this for hydroponic greenhouse cultivation systems and the comparison between shows that the environmental burden comes from high levels of inputs such as fertilizers and structural materials. The reduction in the environmental burden can be improved by using renewable raw materials and renewable energy sources and efficient utilization during cultivation. Considering the complete recycling of structural materials, substrates and composting of plant residues also makes for good practices for environmental sustainability.

Literature cited

Andersson, K., Ohlsson, T., and Olsson, P. (1998). Screening life cycle assessment (LCA) of tomato ketchup: a case study. J. Clean. Prod. *6* (*3-4*), 277–288 http://dx.doi.org/10.1016/S0959-6526(98)00027-4.

Antón, A., Montero, J.I., Muñoz, P., and Castells, F. (2005). LCA and tomato production in Mediterranean greenhouses. International J. Agri Resources Governance and Eco. *4* (*2*), 102–112.

Beccali, M., Cellura, M., Iudicello, M., and Mistretta, M. (2009). Resource consumption and environmental impacts of the agrofood sector: life cycle assessment of italian citrus-based products. Environ Manage *43* (*4*), 707–724 http://dx.doi.org/10.1007/s00267-008-9251-y. PubMed

Cooper, J.M., Butler, G., and Leifert, C. (2011). Life cycle analysis of greenhouse gas emissions from organic and conventional food production systems, with and without bio-energy options. NJAS Wagening. J. Life Sci. *58* (*3-4*), 185–192 http://dx.doi.org/10.1016/j.njas.2011.05.002.

ISO-14040. (1997). Environmental Management - Life Cycle Assessment - Principles and Framework (Geneva, Switzerland: International Organisation for Standardisation ISO. International Standard 14040).

Khoshnevisan, B., Rafiee, M., Omid, M., Mousazadeh, H. and Clark, S. (2014). Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. J. Clean. Prod. *73*, 183–192 http://dx.doi.org/10.1016/j.jclepro.2013.09.057.

NIAES (National Institute for Agro-Environmental Sciences). (2003). Report on the Research Project on Life Cycle Assessment for Environmentally Sustainable Agriculture (Ibaraki, Japan: NIAES).

Romero-Gámez, M., Suárez-Rey, E.M., Antón, A., Castilla, N., and Soriano, T. (2012). Environmental impact of screen-house and open-field cultivation using a life cycle analysis: the case study of green bean production. J. Clean. Prod. *28*, 63–69 http://dx.doi.org/10.1016/j.jclepro.2011.07.006.

Torrellas, M., Antón, A., Ruijs, M., Victoria, N.G., Stanghellini, C., and Montero, J.I. (2012). Environmental and economic assessment of protected crops in four European scenarios. J. Clean. Prod. *28*, 45–55 http://dx.doi.org/10.1016/j.jclepro.2011.11.012.

Williams, A.G., Audsley, E., and Sandars, D.L. (2006). Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. In Main Report, Defra Research Project IS0205 (Cranfield University and Defra).