Evaluation of Energy Use and Some Environmental Impacts for Greenhouse Tomato Production in the High Altitude Tropics

A. Medina, A. Cooman and C.A. Parrado
Centro de Investigaciones y Asesorías Agroindustriales
Universidad de Bogotá
Jorge Tadeo Lozano
Colombia

E. Schrevens
M3-BIORES
Faculty of Applied Bioscience and Engineering
K. Universiteit Leuven
Belgium

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Abstract

Greenhouse cultivation in the high altitude tropics is an important economical activity and the interest to invest in greenhouse technology to improve yield and quality is increasing. The evaluation of the energy use and other burdens associated with protected cultivation have to be accounted for in order to increase sustainability. The aim of this paper was to make a contribution to the applicability of the life cycle assessment (LCA) methodology in high tropics tomato greenhouse production as tool to identify energy use and some environmental impacts, studying a case in the Bogotá Plateau (Colombia). Overall energy costs for tomato production were calculated at 1108.7 MJ·ton⁻¹, which is extremely low when compared to the energy use in northern Europe. The land use indicator was estimated at 38.5 m²·y⁻¹·t⁻¹ and a water consumption of 28 L·kg⁻¹. High potential emissions of N and P were estimated in relation with high concentrations applied in nutrient solutions and an elevated water use. Improvements in tomato yields and water use efficiency, enhancing the level of technology, are the key factors for reducing environmental impact. The adaptation of impact indicators will be necessary to apply LCA methodology in high tropical farming systems.

INTRODUCTION

In Colombia, field grown tomatoes (Lycopersicon esculentum Mill.) are traditionally produced in the temperate and warm regions, between 0 and 2000 m altitude. Nevertheless, greenhouse vegetable production began recently when producers transferred field grown tomato crops to greenhouses in order to improve yield, quality and to reduce risks related with phyto-sanitary problems. The extension of greenhouse vegetable production is currently estimated to be at least 250 ha of which nearly 200 ha are used for tomato (Cooman, 2002). Besides tomato production, the Bogotá Plateau has an important greenhouse area for the production of cut flowers, with approximately 6500 ha and an export value near to US$ 700 million (Asocolflores, 2006). Nowadays there is interest to invest in greenhouse technology, mainly in automatic ventilation and simple heating systems, due to the necessity of increasing climate control for a better pest and disease management.

Although environmental impact of agricultural production is on the agenda of local policy makers, information in this respect is scarce. For regional stakeholders it is important to assess the potential impact of the increase in the level of greenhouse technology, in order to propose strategies to mitigate or reduce those impacts.

Life cycle assessment (LCA) is possibly the most important tool for the analysis of the environmental impacts of human activities. According to ISO standardisation guidelines an LCA study consists of four phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase. In other countries there are several applications of LCA to evaluate or compare environmental impact of agriculture in specific regions or for different crop production systems (Nienhuis and Vreeder, 1996; Mattson, 1999; Mattson and Wallén, 2003; Antón...
and Castells, 2003; Antón and Montero, 2003; Russo and Scarascia, 2005).

Under this perspective, the aim of this study was to make contributions for the applicability of the LCA methodology in tomato greenhouse production in the Bogotá Plateau, Colombia, by giving an overall picture (screening approach) about energy costs and some potential emissions, identifying weak points for the sustainability of the tomato production. A complementary objective was to gain knowledge about resource use and emissions for subsequent studies in this region. The present study is part of a research project that analyzes and enhances agricultural sustainability for protected and unprotected production systems in the high tropics of Colombia and Peru.

**METHODOLOGY**

For the scope of this study, the environmental impact of the production phase was evaluated, considering energy use, land use, water use and some emissions. The transports of inputs, the energy use for harvest, postharvest and for waste management were excluded, as well as aspects related to seed production. The functional unit was defined as 1 ton of tomatoes.

To make an inventory of inputs and outputs of a greenhouse tomato production system in the Bogotá Plateau, specific data were taken for a common greenhouse for tomato production. Four sub-systems were considered: 1) infrastructure, including greenhouse, irrigation system and machinery; 2) inputs for crop management; 3) energy consumption for machinery; and 4) human power.

The typical greenhouse structure can be described as a plastic greenhouse with a fixed open ridge over the complete length of the roof, in combination with plastic walls that can be rolled-up (Fig. 1). In the case studied, the columns that support the frames are made of steel, combined with wooden frames that support the roof. The spacing between spans is 4.5 to 5 m. The greenhouse was equipped with a drip irrigation system with PVC tubes and polyethylene tapes, valves, small accessories and a tank for mixing the nutrient solution.

The crop cycle in Bogotá Plateau takes 32 weeks. The average planting density is 2.8 plants·m⁻², with an average yield of 160 t·ha⁻¹. Indeterminate tomato varieties are generally grown under greenhouse conditions and in the soil. Fertilizers (mainly calcium nitrate, potassium nitrate and sulfate, ammonium phosphate and magnesium sulfate) are applied through the drip irrigation system, 3 o 4 times per week. Pest and disease control is based on integrated pest management practices (De Vis et al., 2000).

Input energy costs were calculated based on specialized literature references: machinery energy inputs and the energy input of steel for structures were taken from Audsley (1996), plastic (polyethylene and PVC) from Worrell et al. (2000), fertilizers from Weidema et al. (1995) and pesticides from Green (1987). The life time for greenhouse structures, wood materials and concrete was estimated based on local experiences. Human labor was estimated on the basis of the number of hours invested for hand labors for crop management and calculated according to Pimentel (1980).

Direct nutrient emissions were calculated as the balance between the total amount of applied elements and the total amount removed by the crop, considering all harvestable and non-harvestable plant parts. Calculations for N-compounds released to the environment were estimated as follows:

- 2% of the total N applied is released to the air as NH₃-N (Audsley, 1996),
- 1.25% of the total N applied is released as N₂O, of which 10% converts to N-NOₓ (Bentrup et al., 2000; Weidema et al., 2000),
- 50% of the difference between the amount of N applied to the soil, minus the sum of N emissions to the air and N removed by the crop, corresponds to the lixiviation of N (adapted from Antón, 2003).
RESULTS AND DISCUSSION

Energy Use
The total energy use was estimated at 1.11 MJ kg\(^{-1}\) tomato produced. This total energy use is higher than the energy use for unprotected vegetables in Europe (Mattson, 1999; Mattson and Wallén, 2003), but much lower than the energy use in greenhouse production in temperate regions. In Dutch greenhouses, 25.7 MJ of heating energy is used per kg (Elings et al., 2005), without considering the energy of infrastructure and inputs. Van der Velden (2004), considers the use of heating energy in Spain, 13 times lower than in Holland (1.97 MJ kg\(^{-1}\)). The low energy costs for the production of tomato in Colombia is a result of the low level of technology and the absence of heating and CO\(_2\) enrichment.

The highest portion of the energy use in Colombia comes from the greenhouse construction with 41.29% of the total energy use (Table 1 and Fig. 2). The major part of this energy is attributed to the steel. The energy corresponding to the use of fertilizers accounts for 29.73%. In the case under study, nutrients were applied based on soil analyses, the average irrigation dose being 2 L·m\(^{-2}\)·d\(^{-1}\). This proportion of energy use is similar to the report of Hatirli et al. (2005), who found that fertilizers accounted for 27.59% of the total energy input in greenhouse tomato production in Turkey. The proportion of energy used by pesticides can be considered relatively high (17.85%). An intensive use of fungicides can be correlated with the absence of a climate control where heating is used to maintain air humidity under a threshold.

The use of labor in the greenhouse production of tomato in Colombia is relatively high, as all the maintenance of the crop is done by hand, as well as all harvest and post harvest activities. Nevertheless, only 3.28% of the total energy input was estimated as coming from labor, lower than the data reported by Hatirli et al. (2005) for the production of greenhouse tomato in Turkey (8.64%).

Land Use
An estimation of the average yearly yield for Colombia, Spain and Netherlands can be set at respectively 26, 30 and 50 kg·m\(^{-2}\)·y\(^{-1}\) (Cooman, 2002; Antón, 2003; van der Velden and Janse, 2004). The corresponding land use indicator as the amount of square meters needed to produce 1 t·y\(^{-1}\) of tomato, was calculated at 38.5 m\(^{2}\)·y\(^{-1}\)·t\(^{-1}\) for the Bogotá Plateau. Since the tomato yield in the high altitude tropics is relatively low, the area needed to produce one ton is nearly two times the area needed in the Netherlands and almost the same when compared to Spain. This situation means that total acreage of arable land needed for tomato production in the cool tropical climate is considerably higher when compared with productions in temperate zones, using high amounts of technology and heating systems. In spite of the available flat land in the Bogotá Plateau, which can be estimated at least at 100 000 ha, the increments in greenhouse area for the production of horticultural crops will have to consider the potential environmental impacts.

Water Use
To produce 1 kg of fresh tomato fruits 28 L water are applied during the 32 weeks of production. This result is similar to a calculated water use of 29 L·kg\(^{-1}\) for a low technology tomato greenhouse in Catalunya, Spain (Antón, 2003). However, De Pascale and Maggio (2005) point out that in unheated Mediterranean greenhouses a tomato crop uses 40 L·kg\(^{-1}\) which is 30% higher than results obtained for the Bogotá Plateau. These authors also indicated that in Northern European greenhouses the level of technology used can increase water use efficiency up to five times. The relatively high water use in the Bogotá Plateau can be justified as the greenhouses are not climatized and have a fixed opening in the roof, combined with the high vapor pressure deficit and the low air pressure at high altitudes. On the other hand, an excess of water affects the use of fertilizers since these are applied in solution, increasing the level of nutrient lixiviation. The improvement of water use efficiency will be an important aspect for increasing the sustainability of the greenhouse production systems.
Plant Nutrient Emissions

Analyses were made of the total N, P and K content in tomato plants at harvest. These values were used for calculating the N, P and K uptake by the fruits and the other plant parts, considering a yield of 16 kg·m⁻² in 32 weeks and a total production of 1209.53 g·m⁻² of dry matter. The differences between the amount of applied fertilizers and the nutrients removed by the crop gave the direct emissions which were estimated at 17.47 g [N]·m⁻², 5.57 g [P]·m⁻² and 9.21 g [K]·m⁻² for the growth cycle of 32 weeks. For a hydroponic tomato production Antón (2003) found 5.7 g [N]·m⁻², 14.8 g [P]·m⁻² and 19.3 g [K]·m⁻² of direct emissions in drainage water for a similar growing period. These results show a higher emission of N compounds in the case of the Bogotá Plateau. Table 2 resumes the potential emissions of N compounds, calculated as described before. The obtained data for NH₃-N, N₂O-N and NOₓ-N were similar to the N emissions indicated for greenhouse tomato cultivated in soil by Antón (2003), who reported 1 g [NH₃-N]·m⁻², 0.62 g [N₂O-N]·m⁻² and 0.062 g [NOₓ-N]·m⁻². The amount of NO₂-N that could be released to soil or water by lixiviation was higher in Colombia, 8.72 g·m⁻², compared with 3 g·m⁻² pointed out by Antón (2003). This implicates a risk of eutrophication, depending on specific soil conditions and other factors in the Bogotá Plateau.

In the case of P, high doses are used as the predominant soil type of the Bogotá Plateau is classified as an Andosol. According to Malagón et al. (1995), these soils are characterized by a P-fixing capacity of more than 80%. High doses are often recommended in order to avoid P deficiency symptoms. However, surplus of P in the soil and its environmental effects have to be measured in the Bogotá Plateau. Antón (2003) indicates that the soils of Valencia and the water used for irrigation are characterized by a high calcium content and a high pH, causing P immobilization. No emission of P was reported for soil cultivation. A similar situation could occur in the Bogotá Plateau because of the high P-fixing capacity of the predominant soil types.

CONCLUSIONS

Among the most relevant results of this study are the very low energy use, associated with the low level of technology and the absence of heating systems, and the high land and water use for the production of greenhouse tomato in the Bogotá Plateau. The highest nutrient emission is attributed to the lixiviation of NO₃-N, while the risk of lixiviation of phosphorus is very low.

The improvement of greenhouse tomato yields could contribute to reduce the environmental impacts related with energy use and the depletion of natural resources. This improvement could be fulfilled through the increment of the technological level and adapting technologies for a more efficient land and water use. However, the increase in technological levels often enhances energy use (Velden and Janse, 2004). A careful balance between the expected yields and energy use should be carried out. For this purpose, greenhouse climate models, combined with plant growth models, can be useful tools (Cooman, 2002).

One of the crucial results of this study where the tomato production under greenhouse conditions is analyzed is the inefficient use of N compared with Mediterranean greenhouses and water compared with Northern European greenhouses. High water applications conducd to high doses of N, P and K. It is necessary to increase water use efficiency through better management practices, using tools to monitor the soil water balance, climate and the needs of the crop. The surplus of applied N, P and K enhances the risk of emissions to air, water and soil, resulting in potential environmental damages such as acidification, eutrophication, human toxicity, eco-toxicity, climate change and others. Efficient water management will be a major key variable to manage, in order to reduce several environmental impacts.

The application of the LCA methodology in order to assess environmental impacts in tropical farming systems is recommended as one of the cornerstones of sustainability management. However, environmental impact indicators should be adapted to tropical or local conditions such as the local construction materials and energy sources. Data quality
will have to be considered, uncertainty on the data will have to be estimated.

Greenhouse farming systems are labor-intensive and a model for the estimation of the labor requirements per unit produced can be an indicator of vulnerability as labor costs increase. Also have social implications to be considered as greenhouse horticulture is one of the main rural employment opportunities in the Bogotá Plateau.

Literature Cited

Tables

Table 1. Energy inputs per hectare and per ton of tomato produced, for the production of greenhouse tomato in the Bogotá Plateau (Colombia).

<table>
<thead>
<tr>
<th>Item</th>
<th>Energy input (MJ/ha)</th>
<th>Energy input (MJ/ton)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse</td>
<td>73242.75</td>
<td>457.77</td>
<td>41.29</td>
</tr>
<tr>
<td>Irrigation equipment</td>
<td>1308.77</td>
<td>8.18</td>
<td>0.74</td>
</tr>
<tr>
<td>Machinery</td>
<td>158.67</td>
<td>0.99</td>
<td>0.09</td>
</tr>
<tr>
<td>Energy for infrastructure</td>
<td>74710.18</td>
<td>466.94</td>
<td>42.12</td>
</tr>
<tr>
<td>Plant guiding</td>
<td>1716.62</td>
<td>10.73</td>
<td>0.97</td>
</tr>
<tr>
<td>Fertilizers</td>
<td>52739.35</td>
<td>329.62</td>
<td>29.73</td>
</tr>
<tr>
<td>Pesticides</td>
<td>31661.60</td>
<td>197.89</td>
<td>17.85</td>
</tr>
<tr>
<td>Energy for inputs</td>
<td>86117.57</td>
<td>538.23</td>
<td>48.55</td>
</tr>
<tr>
<td>Greenhouse building</td>
<td>1512.42</td>
<td>9.45</td>
<td>0.85</td>
</tr>
<tr>
<td>Soil preparation</td>
<td>1339.89</td>
<td>8.37</td>
<td>0.76</td>
</tr>
<tr>
<td>P &amp; D Control</td>
<td>719.73</td>
<td>4.50</td>
<td>0.41</td>
</tr>
<tr>
<td>Watering</td>
<td>2250.49</td>
<td>14.07</td>
<td>1.27</td>
</tr>
<tr>
<td>Energy for machinery operation</td>
<td>10734.696</td>
<td>67.09</td>
<td>6.05</td>
</tr>
<tr>
<td>Human power</td>
<td>5822.53</td>
<td>36.39</td>
<td>3.28</td>
</tr>
<tr>
<td>Total energy input</td>
<td>177384.98</td>
<td>1108.66</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Table 2. Composition of the nitrogen emissions estimated for a greenhouse tomato crop in the Bogotá Plateau (Colombia) during a 32-week period.

<table>
<thead>
<tr>
<th>Compound</th>
<th>g m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃-N to air</td>
<td>1.24</td>
</tr>
<tr>
<td>N₂O-N to air</td>
<td>0.78</td>
</tr>
<tr>
<td>NOₓ-N to air</td>
<td>0.08</td>
</tr>
<tr>
<td>NO₃⁻-N to water</td>
<td>8.73</td>
</tr>
</tbody>
</table>
Figures

Fig. 1. Typical greenhouse for the production of tomato in the Bogotá Plateau.

Fig. 2. Distribution of the energy use (%) for the production of greenhouse tomato in the Bogotá Plateau. Overall energy consumption was 1108.7 MJ t\(^{-1}\). The activities included greenhouse construction, soil preparation, pest and disease control and irrigation.