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Joint Life Cycle Assessment and Data Envelopment Analysis for the benchmarking of environmental impacts in rice paddy production

Ali Mohammadi [a,b,*], Shahin Rafiee [a], Ali Jafari [a], Alireza Keyhani [a], Tommy Dalgaard [b], Marie Trydeman Knudsen [b], Thu Lan T. Nguyen [b], Robert Borek [c], John E. Hermansen [b]

[a] Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran
[b] Aarhus University, Department of Agroecology, Blichers Allé 20, P.O. Box 50, DK-8830 Tjele, Denmark
[c] Department of Agrometeorology and Applied Informatics, Institute of Soil Science and Plant Cultivation – State Research Institute (IUNG-PIB), Czartoryskich 8 Str., 24-100 Puławy, Poland

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ABSTRACT

The combined implementation of Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) has been identified as a suitable tool for the evaluation of the environmental and economic performance of multiple similar entities. In this study, a total of 82 rice paddy fields for spring and summer growing seasons in north of Iran were assessed using a combined LCA and DEA methodology to estimate the technical efficiency of each farmer. Furthermore, the environmental consequences of operational inefficiencies were quantified and target performance values benchmarked for inefficient units so that eco-efficiency criteria were verified. Results showed average reduction levels of up to 20% and 25% per material input for spring and summer systems, leading to impact reductions which ranged from 8% to 11% for spring farms and 19% to 25% for summer farms depending on the chosen impact category. Additionally, the potential economic savings from efficient farming operations were also determined. The economic results indicate that an added annual gross margin of 0.045 $ per 1 kg rice paddy could be achieved if inefficient units converted to an efficient operation.

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1. Introduction

Rice is known as a staple human food source in many areas of Iran, where the average per capita consumption of rice is 100 g/day which ranks Iranian people as the 13th biggest rice consumers (Hormozi et al., 2012). Iran has to import 1.7 Mt rice per year to supply the domestic market which makes Iran the second largest rice importing country after Philippine, measured per capita (Pishgar-Komleh et al., 2011). Agricultural organizations in Iran have started the attempts toward self-sufficiency in rice production and statistics show that the annual production of this crop has increased in the last decade and achieved 2.3 Mt in 2010 (FAO, 2010).

Thus, rice production plays a key role in food security in Iran but there are increasing concerns regarding Greenhouse Gas (GHG) emissions related to cultivation of rice (Wenjun et al., 2006). Studies on environmental effects from flooded rice farming have particularly considered emissions of methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3) (Linquist et al., 2012a; Hokazono and Hayashi, 2012). CH_4 emissions in rice systems result in a high global warming impact relative to other crops, which contribute 10–13% of total methane emissions in the world (Neue, 1997). In some countries including Iran, besides the emissions, non-renewable energy consumption and water use are also major concerns in rice farms mainly due to irrigation operation based on pumping systems. Furthermore, chemical fertilizers are among the most important inputs for increasing rice yield (Mohammadi et al., 2014), whereas it contributes to a wide range of soil and water pollution.

Therefore efforts to identify pathways for mitigating environmental risks are required. Plenty of works is found on the environmental impact assessment for rice fields in countries such as Taiwan (Yang et al., 2009), China (Zhang et al., 2010), Japan (Koga and Tajima, 2011; Hokazono and Hayashi, 2012), Italy (Blengini and Busto, 2009) and USA (Linquist et al., 2012b), but in Iran very little attention has been paid to the GHG emissions from the

* Corresponding author. Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran. Tel.: +98 2612801011; fax: +98 2612808138.
E-mail addresses: Mohammadia@ut.ac.ir, mohammadia2011@gmail.com (A. Mohammadi), shahinrafiee@ut.ac.ir (S. Rafiee).

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agricultural sector. Karimi et al. (2012) estimated that groundwater pumping for farm irrigation annually consumes 20.5 billion kWh electricity and 2 billion liters of diesel and contributes to 3.6% of the total CO_2 emission of Iran. The improvement of irrigation practices can result in 40% reduction in energy use and consequently carbon emission of groundwater consumption. In another work, for wheat production, average GHG emissions of 1137 kg CO_2 eq. ha^{-1} and 291 kg CO_2 eq. t^{-1} were calculated (Soltani et al., 2013). Hence it is important to perform works to suggest options for reducing environmental costs in agricultural systems of Iran, particularly rice paddy since the harvested area has been increased in recent years (FAO, 2010).

In this regard, Life Cycle Assessment (LCA) is one of the best methodologies for the environmental consequences of agri-food systems, by recognizing energy and inputs used as well as direct and indirect GHG emissions (Cherubini, 2010). LCA is commonly applied to assess all environmental impacts associated with a product, process or activity by accounting and evaluating the resource consumption and the emissions (Chang et al., 2012). LCA can be used to compare two or more systems or a system based on a reference. This methodology can also be combined with Data Envelopment Analysis (DEA) in order to face the assessment of multiple inputs and outputs for a large number of similar facilities. DEA is a performance measurement methodology used to quantify the comparative efficiency of a set of similar entities named Decision Making Units (DMUs) with multiple input/output data by some specific mathematical programming models (Samuel-Fitwi et al., 2012). In the current study, the results of the original life cycle impact assessment (LCIA) are compared to the computed target life cycle impact assessments (LCIA). This results in reduced environmental impacts for the calculated targets because for the same amount of output, a lower amount of inputs will be consumed (Samuel-Fitwi et al., 2012). Several recent studies applied the LCA + DEA approach to improve the operational and environmental efficiency and enhance economic performance (Lozano et al., 2010; Iribarren et al., 2011; Vázquez-Rowe et al., 2012a; Mohammadi et al., 2013).

In literature there are a few studies on LCA application on Iranian agriculture (Khoshnevisan et al., 2013a,b), but no work exists regarding the environmental impacts of rice paddy cultivation in this country. The purpose of this study was to assess the environmental impacts for rice paddy production in the different growing seasons and investigate improvement options by using an LCA and DEA approach. We use this methodology to achieve operational benchmarking and productive efficiency while evaluating the environmental performance of the rice paddy farms. The study also estimates the economic gains from the optimized values of physical inputs.

2. Materials and methods

2.1. Study area, field selection and farming practices

North of Iran has been recognized as the best area for rice cultivation in Iran and representing over 80% of the national rice production. The present study was conducted in the Gorgan region (36°83′ N and 54°48′ E) of the Golestan province, located in north of Iran. In the study year, the average annual rainfall was 528 mm, maximum and minimum temperatures were 32 °C and 6 °C, respectively.

The data for the study were collected from 82 rice paddy farmers in 10 villages in 2010. Farmers were asked to fill out a questionnaire (Mobtaker et al., 2010; Mohammadi et al., 2014) to characterize their usual field operation (pesticide and fertilizer use, tillage and harvesting) growing season (spring or summer), yield and economic information. Rice paddy farms in this region differed in growing season. Therefore, in order to work with homogenous groups, the farms were divided into two; spring and summer groups. Spring fields were cultivated rice paddy from the mid-April up to mid-September; and summer fields were sown it the first of June and harvested at end of October including seedling period. The length of seedling period for both the spring and summer fields varied from around 30–40 days.

2.2. Selected DEA model

DEA is a well-known mathematical procedure that uses a linear programming (LP) technique to assess the efficiency of Decision Making Units (DMUs) or units of assessment. DEA allows for the measurement of comparative efficiency for a group of DMUs that use inputs in the form of different scales because the model adjusts with the ratio of the weighted sum of outputs to the weighted sum of inputs. Therefore the results could clearly be presented and simply compared efficient and inefficient DMUs. An input-oriented slacks-based measure of efficiency model with constant returns to scale (CRS) was selected for the current study. The selection of an input-oriented model for a LCA + DEA work is due to this approach focuses on reducing input utilization and its associated environmental costs as much as possible (Vázquez-Rowe and Tyedmers, 2013; Mohammadi et al., 2013). CRS were chosen since paddy farms operate within a competitive market. Before 2010, the agricultural sector of Iran was supported by the government and the farm inputs were subsidized for the producers. Over this period, agricultural produce market couldn't be assumed as a free market, but in recent years all subsides allocated to energy and farm inputs have been removed gradually. Hence, it has been assumed that paddy farms work in a competitive market, therefore the CRS approach can be implemented for this case (Mohammadi et al., 2013).

The units of assessment chosen for this study are rice paddy fields. The most relevant farm input and output data (DEA matrices) for both the spring and summer systems as the sample of 82 rice paddy farms is gathered in Table 1. All the selected operational items for analysis are assumed to be independent of each other. Hence, land used was not involved since its minimization would influence other inputs, like diesel or fertilizers. Likewise, direct emissions to the different compartments are not comprised in the DEA matrix, given their direct proportion to some of the inputs included in the matrix. Thus, these emissions are indirectly minimized through direct minimization of the associated inputs (Lozano et al., 2009; Vázquez-Rowe et al., 2010). In order to provide the study with a stronger socioeconomic dimension, other inputs such as labor are included as an additional DEA input in the matrix (Vázquez-Rowe et al., 2012a).

2.3. Technical Efficiency (TE) and Super efficiency (SE)

The basic feature of DEA is that the Technical Efficiency (TE) score of each DMU depends on the performance of the sample of which it is a part (Martínez and Silveira, 2012). TE is defined as the ability of a DMU to produce maximum output given a set of inputs and technology level, and its score calculated by the ratio of sum of weighted outputs to the sum of weighted inputs.

The efficiency score (θ) in the presence of multiple- input and -output factor is calculated as (Mousavi-Avval et al., 2011; Omid et al., 2011):

$$\mathrm{TE} = \frac{\text{weighted sum of outputs}}{\text{weighted sum of inputs}} \tag{1a}$$

or mathematically as:

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