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Solar Powered Automated Pipe Water Management System, Water Footprint and Carbon Footprint in Soybean Production

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Solar Powered Automated Pipe Water Management System, Water Footprint and Carbon Footprint in Soybean Production

Satyanto K S[1], Abang Z E[1], C Arif[1] and M Yanuar J P[1]

[1] Department of Civil and Environmental Engineering, Bogor, Indonesia

E-mail: saptomo.sk@gmail.com

Abstract. An automatic water management system for agriculture land was developed based on mini PC as controller to manage irrigation and drainage. The system was integrated with perforated pipe network installed below the soil surface to enable water flow in and out through the network, and so water table of the land can be set at a certain level. The system was operated by using solar power electricity supply to power up water level and soil moisture sensors, Raspberry Pi controller and motorized valve actuator. This study aims to implement the system in controlling water level at a soybean production land, and further to observe water footprint and carbon footprint contribution of the soybean production process with application of the automated system. The water level of the field can be controlled around 19 cm from the base. Crop water requirement was calculated using Penman-Monteith approach, with the productivity of soybean 3.57t/ha, total water footprint in soybean production is 872.01 m^3/t. Carbon footprint was calculated due to the use of solar power electric supply system and during the soybean production emission was estimated equal to 1.85 kg of CO^2.

1. Introduction

Soybean water saturation cultivation is one of the cultivation techniques that has one objective of increasing sub-optimal wetland productivity while preserving it from degradation due to over drainage. It is important to provide appropriate field water level as the root may not be submerged under the water for a long time but in the other hand it may not be too low that will stop the capillary rise to keep water available in the soil. One method that we are proposing is by using perforated pipes that is laid below the surface. The perforated pipe will be water line for drainage and/or irrigation depends on the case.

Irrigation automation refers to the operation of system that minimized manual intervention in irrigation, which can be conducted in small area or in a large area segmented into smaller parts. The segments are called irrigation block and receive water regarding the available discharge as mention in Anitha [1]. The performance of automatic irrigation had been increased by the introduction of microcontroller which reduces the complicity of circuit design and the cost while upgrading the system is become easier [2]. There are many additional sensors and components that were designed for direct interfacing with microcontroller that ease the design and modification [3].

The use of electricity in electromechanical control system like automatic irrigation however causes carbon footprint due to equivalent CO2 emission for every unit usage of electricity that added in soybean production at the implemented land. Life cycle assessment (LCA) produces complete figure from input and output of components: air pollution emission, water utilization, wastewater generation, energy consumption and greenhouse gasses emission. To determine carbon footprint, LCA estimate the emitted or produced greenhouse gasses gas in every step identified for product life cycle, technically known as greenhouse gases calculation [4].

Water footprint is a measure of humanity's appropriation of fresh water in volumes of water consumed and/or polluted in the production process. Water footprint of a province consist of internal and external. Internal means the annual volume of water sourced from the province that is consumed to produce crop for the local population. While external means if the water was originated from outside of the province as mentioned by Hoekstra and Chapagain [5]. Consumers water footprint is also divided into direct and by consumption of agricultural and industrial product. In Indonesia only 3% of water footprint from industrial product, and greater portion is from agriculture. Water footprint and carbon footprint can describe how well we use and conserve resources for our production activity, and the method we choose will add particular water footprint and carbon footprint to our product.

The objective of this study are to develop a solar-powered automation control applied to pipe irrigation and drainage system which was set below the soil surface using perforated pipe and use it in trial and to estimate the contribution of water footprint and carbon footprint originated from soybean production related to automatic water management.

2. Material and methods

2.1. *Water management setting*

The field for soybean was made into beds having width of 4 m and height of 30 cm from the base. Each bed was separated by small 30 cm width and depth channel where perforated PVC pipe was laid at the bottom. The pipes connected to unperforated collector pipe which will transmit water to outlet. Figure 1 shows the water management setting of the field and figure 2 shows pipes installation with coconuts fiber to tighten the pipes to the bottom of the channel.

At the inlet an electric motorized valve was installed to control flow of water into the field. The operation of the valve was done automatically with controller. With perforated pipes position below the bed, they also functioned as drainage. Both inlet and outlet were attached with flowmeter to observe the amount of inflow and outflow.

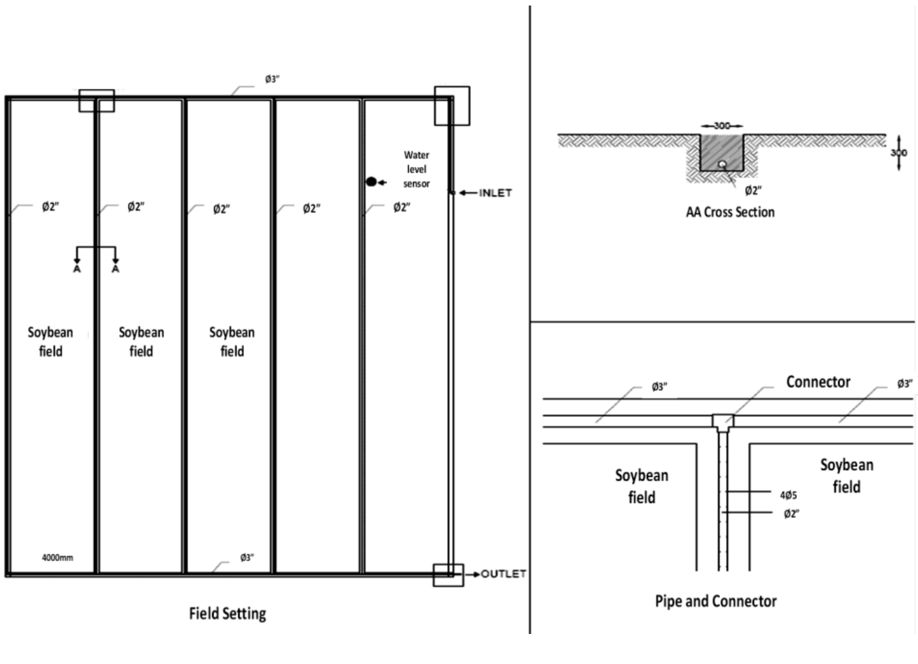

Figure 1. Field Setting

Figure 2. Pipes installation

2.2. *Solar power automated irrigation system*

Automatic irrigation system that was implemented in the study is the solar powered automatic irrigation system that was developed for rice field (figure 3), with modification in water delivery system to the field by using perforated pipe. The system is fully operated by using battery continuously 24 hours. During daytime the battery is charged by solar panel to ensure the availability of energy.

Solar power generated electricity can save energy consumption of more than 35% [6]. Another modification that was made is the use of Raspberry Pi minicomputer, instead of microcontroller. The system is responsible to read water level with water level sensor and to open or close irrigation by operating motorized valve automatically.

There are two setpoints that were used, which are upper setpoint and lower setpoint. Water from reservoir will flow through the pipes as water level fall below lower setpoint and irrigation will be stopped if water level reach the higher setpoint. This method was chosen considering its simplicity and effectiveness in providing appropriate level for the land.

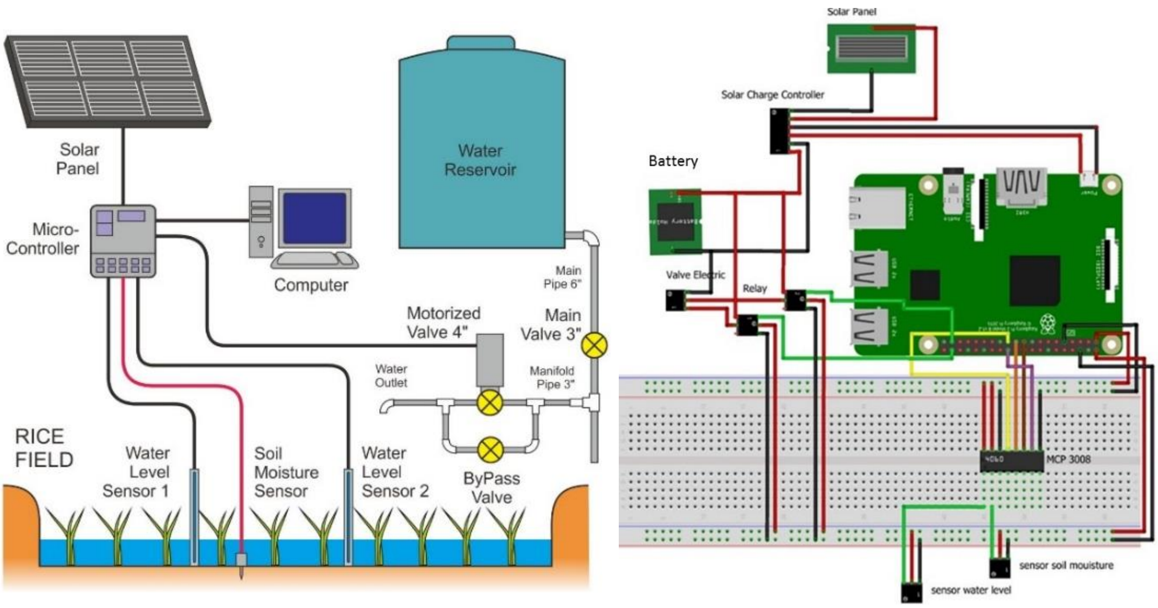

Figure 3. Solar powered automatic irrigation system setting and Raspberry Pi controller prototyping schematic

The components of the automatice controller are:

1. Raspberry Pi
2. Project Board
3. Water Level sensor
4. Soil Moisture Sensor
5. Solar Panel
6. Solar Charge Controller
7. Magnetic Relays
8. Electric Valve

Raspberry Pi is a credit card sized miniPC device having system of Broadcom BCM2835 chip (SoC), which includes ARM1176JZF-S 700 MHz to 1 GHz, VideoCore IV GPU [7]. All sensors and actuators are connected and controlled by this device. Figure 4 shows the installation of sensors and valve and figure 5 shows the experimental land during soybean cultivation experiment.

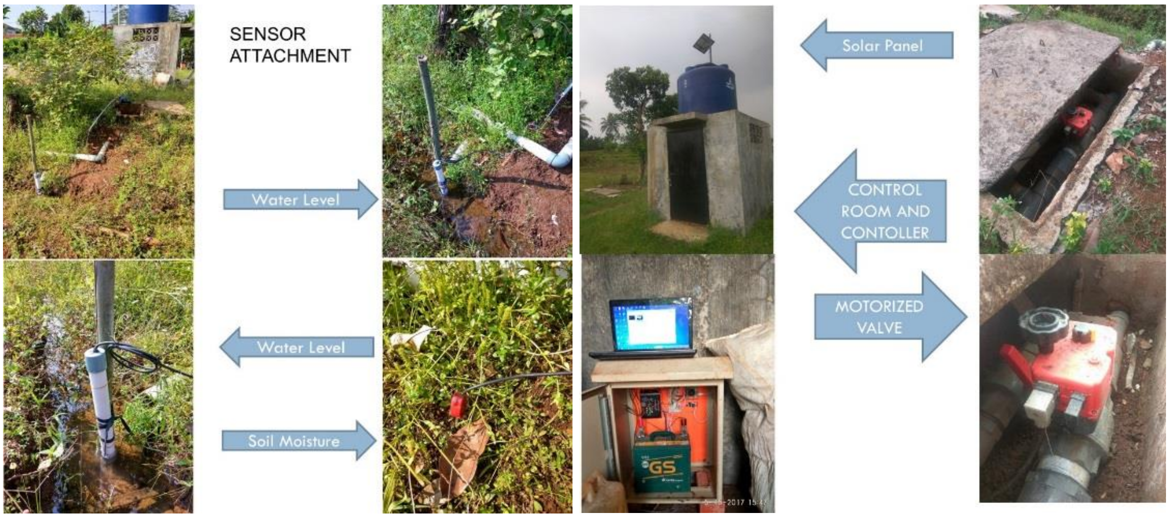

Figure 4. Sensors and Valve

Figure 5. Experimental land

2.3. *Water Footprint Calculation*

As it was described by Hoekstra et al. [8], water footprint is total water use to produce a product. The calculation of water footprint is divided into green water footprint, blue water footprint, and grey water footprint. They describe the amount of rainwater and irrigation water that were used and amount of water to clean the pollution resulted during the production activity, in volume of water per unit of product mass (m^3/t). This can be calculated using equation 1.

$$WF = WF_{green} + WF_{blue} + WF_{grey} \tag{1}$$

Where :

WF	: *Water footprint* (m^3/ton)
WF_{green}	: Green *Water footprint* (m^3/ton)
WF_{blue}	: Blue *Water footprint* (m^3/ton)
WF_{grey}	: Grey *Water footprint* (m^3/ton)

Each green, blue and grey water footprint can be calculated with equations 2, 3 and 4. In this study, crop water use (CWU) was estimated by at first determining reference evapotranspiration (ETo). This was done by using FAO standardize method to calculate ETo [9]. ET_{green} and ET_{blue} are the consumptive water use of the plants regarding to it source of water: green (rainwater) and blue (surface/groundwater).

$$WF_{green} = \frac{CWU_{green}}{Y} \tag{2}$$

$$WF_{blue} = \frac{CWU_{blue}}{Y} \tag{3}$$

$$WF_{grey} = \frac{(\alpha \times AR)(C_{max} - C_{nat})}{Y} \tag{4}$$

where

WF_{green}	: green water foot print (m^3/ton)
WF_{blue}	: blue water foot print (m^3/ton)
WF_{grey}	: green water foot print (m^3/ton)
CWU_{green}	: crop water use/ET_{green} (m^3/ha)
CWU_{blue}	: crop water use/ET_{blue} (m^3/ha)
α	: times the leaching-run-off fraction (-)
AR	: chemical application rate to the field (kg/ha)
C_{max}	: maximum acceptable concentration (kg/m^3)
C_{nat}	: natural concentration for the pollutant considered (kg/m^3)
Y	: crop yield (ton/ha)

2.4. *Carbon Footprint Calculation*

Carbon footprint is the total greenhouse gas that is emitted or produced from production process of a product. We can distinguish the calculation into primary carbon and secondary carbon footprint. In this study, only the later mentioned was implemented because there was no fossil fuel being used in water management process. Instead, electricity was used which CO2 emission is calculated as equation 5 [10].

$$CO_2 = EF \text{ x electricity consumption} \tag{5}$$

where:

CO_2 = emission of CO_2 (kg CO_2)
EF = emission factor (kg CO_2/kWh)
Electricity consumption = Quantity of used electrical energy (kWh)

3. Result and discussion

3.1. *Control performance*

Result of automatic irrigation operation is shown in figure 6 which depicts upper and lower setpoints, fluctuation of actual water level and the state of irrigation (valve). Valve's state was given value 0 or 1, which mean the valve is closed to stop irrigation or is opened to apply irrigation. It is clearly seen that valve's state became 1 when water level below lower setpoint and was kept open until water level reaches the upper setpoint. After upper setpoint was reached or exceeded valve's state turn to 0 which meant irrigation was stopped and water level will gradually decrease.

There were events when water level suddenly increases above upper setpoint, which happened as rain fallen. This sudden event would trigger the control system to close irrigation valve. In this case water level was not gradually decrease but rather drop due to drainage.

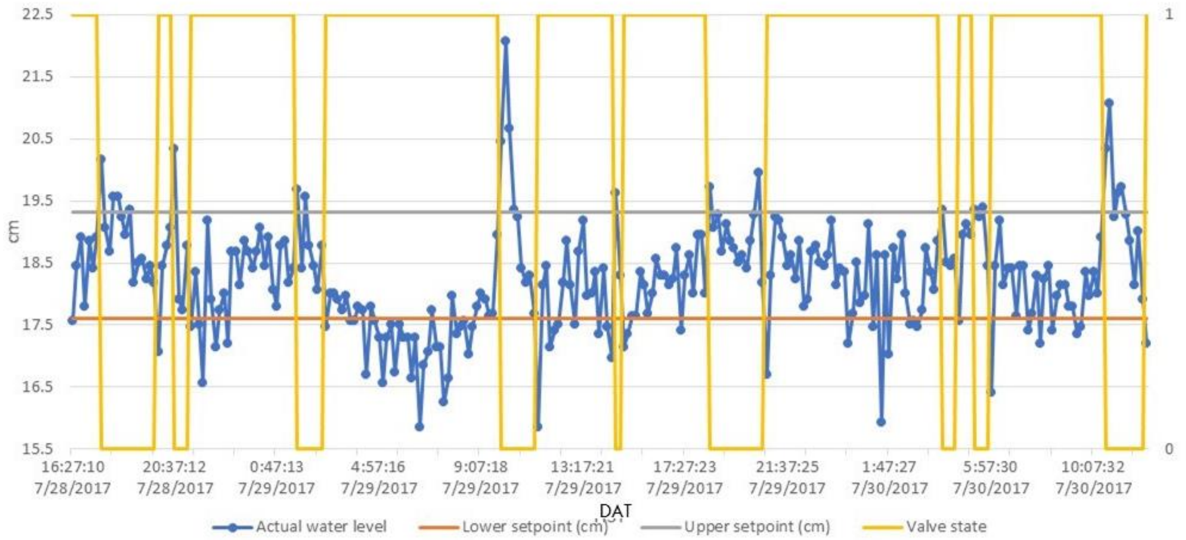

Figure 6. Automatic irrigation control performance

3.2. *Water Footprint*

Water footprint was obtained from the amount of water applied to provide crop water requirement which originated from seepage, rainfall and irrigation. Effective rainfall was used as part of rainfall that can be held by soil pores and available for crops, which are always less than total rainfall. Seepage is determined as water that comes out from the soil, although it was originated from the adjacent irrigated field due its higher elevation. The amount of seepage is in accordance to rainfall, the greater rainfall drove greater seepage inflow. This stage of study was conducted during rainy season, and water input to the land through seepage was dominant. Figure 7 shows monthly evapotranspiration, effective rainfall and seepage during the observation.

Table 1. Calculation of crop water use (CWU)

Month	Min Temp °C	Max Temp °C	RH %	Wind Speed km/day	Sunshine hours	Radiation MJ/m^{2}month	ETo Mm/month
March	18.80	34.00	85.35	26.13	4.86	529.00	108.89
April	18.00	34.30	87.67	20.73	3.63	420.90	87.65
May	22.20	42.90	87.42	1.42	5.73	484.70	101.09
June	22.30	34.00	85.40	1.5	6.40	157.70	31.73

Due to unavailability harvest data during preparation of this report, soybean productivity was assumed following Ghulamahdi et al. [11], for water saturated soybean production: 3.57 t/ha. Therefore, water footprint added to soybean production from this stage are as shown in table 2 and 3 which shown grey water footprint. Water footprint of seepage was difficult to be categorized as it came from the adjacent field through subsurface flow. The origin of water itself was either from irrigation or rainfall, thus for the moment we let it not be defined as green or blue. Here green water footprint was found 433.74 m^3/t, and water footprint for seepage is 303.68 m^3/t.

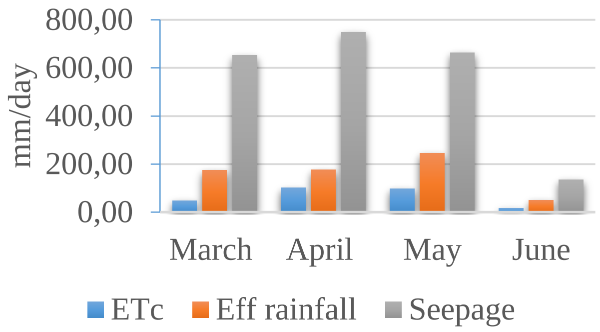

Figure 7. ET, Rainfall and Seepage

Table 2. Calculation of green and blue water footprint

Month	ETc mm/day	CH eff mm/day	Seepage mm/day	CWU green m^3/ha	CWU seepage m^3/ha	Yield t/ha	WF green m^3/t	WF seepage m^3/t
March	48.33	174.14	651.76	342.12	141.14	3.57	95.83	39.54
April	100.80	175.64	749.41	599.61	408.36	3.57	167.96	114.30
May	98.27	245.60	662.65	511.71	470.98	3.57	143.33	131.93
June	15.87	50.24	135.94	95.00	63.65	3.57	26.61	17.83

Table 3. Calculation of grey water foot print

Mineral	AR (kg/ha)	α	Cmax (μg/L)	Cmax (kg/L)	Cnat (mg/L)	Cnat (kg/m^3)	GWfp (m^3)
N	0.3	$1.42x10^{-1}$	13000	$1.30\ x10^{-2}$	0.26	$2.60\ x10^{-4}$	3.35
P	0.2	$2.34\ x10^{-1}$	20	$2.00x\ x10^{-5}$	0.01	$1.00\ x10^{-5}$	467.73

Grey water footprint of soybean was estimated from Nitrogen and Phosphorus content in manure and fertilizer. Greywater footprint for N and P are 0.96 m^3/t dan 133.64 m^3/t and total grey water footprint is 134.59 m^3/t. In summary, water footprint for soybean from during cultivation period was 872.01 m^3/t.

Arena et al. [12] presented soybean water footprint in Argentina with and without irrigation are 2,572.2 m^3/t and 2,440.7 m^3/t with productivity 3.2 t/ha and 2.8 t/ha. In America, Mubako dan Christoper [13] had shown that soybean water footprint is between 651 m^3/t to 2,281 m3/t. The difference of water footprint in different country is influenced by geographical condition, climate, the length of cultivation period and the productivity. In this case, our study result is close to that in America. However since this was done only in one trial, and this study only considers the period after planting to harvest, and the exact harvest had not been quantified yet, we will need more trial and extensive data before we can conclude the right figure of water footprint of soybean in water-saturated soil cultivation.

3.3. *Carbon footprint*

Carbon footprint calculation was based on the amount of electricity of the whole automation system with solar electricity generation. Postnote [15] suggested that solar panel emits 58 g CO_2/kWh it produced, this is based Lifecycle CO_2 emissions for UK photovoltaic power systems with current technology. During non-irrigation period, when automatic system was not operating, only monitoring function controlled by the controller, total daily consumption for the whole system is 0.31 kwh per day and thus emission for 102 days soybean cultivation 1.85 kg CO_2.

Table 4. Electricity consumption of automatic system components

Device	Voltage (V)	Current (A)	Power (watt)	Operation	Time (hour)	Energy Consumption (kWh)
Raspberry pi 3 model B	5	2.5	12.5	1 day	24	$3.00\text{x}10^{-01}$
Sensor E tape			0.5	1 day	24	$1.20\text{x}10^{-02}$
Sensor VH400 Vegetronix	3.5	0.012	0.042	1 day	24	$1.01\text{x}10^{-03}$
Relay (1)			0.15	1x valve opening	$8.33\text{x}10^{-03}$	$1.25\text{x}10^{-06}$
Relay (2)			0.15	1x valve closing	$8.33\text{x}10^{-03}$	$1.25\text{x}10^{-06}$
Valve Valworx 561086	12	2.1	25.2	1x valve opening or closing	$8.33\text{x}10^{-03}$	$2.10\text{x}10^{-04}$

By analyzing control performance data shown in figure 6 electricity that was used by actuators (relays and valve) can be estimated. The time that was required by water level to decrease to lower setpoint and increase again to upper setpoint is 2 hours 30 minutes, where valve opened and closed once. During 102 days, valve opened and closed up to 1958 times. One rotation of electric emitted carbon emission of 24.1 g. Assuming automatic irrigation would operate each day the same as it' performance in the trial, during the production period, the system will produce 1.88 kg of CO_2 equivalent emission. Table 4 shows the detail energy consumption and carbon emission of the automatic irrigation.

Irrigated land produced emission more than the non irrigated one due to its larger electricity consumption for operation of relays and valve. Esteves et al [15] revealed that soybean irrigation in Brazil produced 6.04 kg CO_2. The larger figure compared to our case is due to the use of diesel fuel, not solar electricity. Therefore carbon footprint added to soybean production can be minimized by using solar-powered automatic irrigation system.

4. Conclusions

Automatic water management system had been developed and water level of the field was controlled within the setpoints range (around 20 cm from base). With productivity of soybean 3.57t/ha, total water footprint in soybean production is 872.01 m^3/t. Carbon footprint due to the use of solar-powered system was estimated equal to 1.85 kg of CO_2 when irrigation is not operating and 1.88 kg of CO_2 if the field automatically irrigated.

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