KEYNOTE ADDRESS

WATER, FOOD AND ENERGY SECURITY IN AN EARTH SYSTEM UNDER STRESS

Joachim Müller

Institute of Agricultural Engineering, Tropics and Subtropics Group, University of Hohenheim, Stuttgart (Germany)
Email: joachim.mueller@uni-hohenheim.de

ABSTRACT

Global population growth going along with a growing demand for a higher living standard exerts increasing stress on natural resources like water, land and energy. Excessive use of fossil energy depleted already a good part of petroleum and gas resources with the known consequences of climate change caused by greenhouse gas emissions. For guaranteeing water, food and energy security for the entire population also for future generations, a shift in paradigm is required: an era of steady extension and intensification has to be followed by an era of increasing efficiency and sufficiency. In times of increasing urbanisation, rural areas are playing a crucial role in this process. Beyond the traditional role in providing safe food in adequate quantities under sustainable use of land and water, rural regions are key stakeholders in renewable energy provision. Solar, wind and hydropower are characterised by low areal density and, hence, are asking for decentral conversion. The complexity of the water-food-energy nexus does not encourage simple "one size fits all" solutions. Various local approaches based on indigenous experience and knowledge enforced by state-of-the-art science and technology can add to a toolbox for addressing the challenges of an earth system under stress. Some recent examples from own research are presented.

Keywords: Irrigation, postharvest technology, renewable energy.

WATER-FOOD-ENERGY NEXUS

Water, food and energy are essential resources of human life and they are interlinked in various ways. To guarantee food security for a growing world population, efficiency of agricultural production has to be intensified by irrigation. Irrigation requires fresh water of suitable quality and energy for water conveyance and distribution in the field. The growth of the world population is reflected by global water consumption. However, the allocation of the water resources to domestic, agricultural and industrial sector is regionally different. While the water demand of industry is predominant in the USA, the requirements of agriculture clearly account for the largest share in the developing countries. Water and energy is also required in postharvest food processing and preparation of meals. Far above domestic and agricultural demands, energy has become a driving force in industrial development. Gross domestic product (GDP) shows a positive correlation with energy consumption (Fig. 1). Industrialized countries have a high gross domestic product and high energy consumption per resident, whereas both parameters are low in developing countries. It is disputable whether increased energy consumption is the cause or the effect of development because they are ultimately both part of a positive feedback loop.

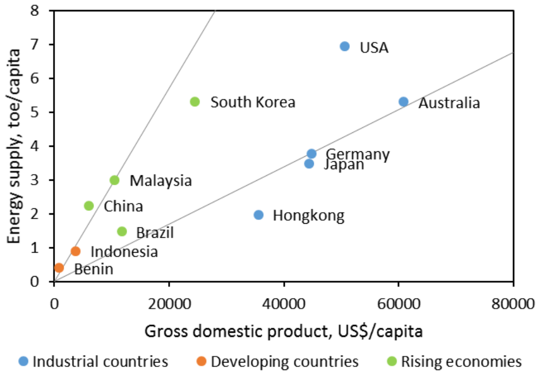

Figure 1. Energy supply vs. gross domestic product (GDP) for selected countries; inclination of grey lines show energy supply per GDP (toe/US$) for Malaysia and Germany; data IEA 2014 [1].

Specific energy consumption per GDP varies among countries, which is represented by the inclination of the origin lines in Fig. 1. For instance, Malaysia shows a higher value with 0.29 toe/1000 US$ than Germany with 0.08 toe/1000 US$. This means that Malaysia is investing more energy per economic output. In China the specific energy consumption is even less favourable with a value of 0.37 toe/1000 US$. The reason is not only different energy efficiency, but also the economic structure. Economies that are widely based on the service sector, are less energy dependent than those with energy-intensive raw material industry. Nevertheless, for sake of CO_2 emission reduction, energy efficiency has to be increased and the share of renewable energy has to be increased. Various local approaches based on indigenous experience and knowledge enforced by state-of-the-art science and technology can address the challenges. Some recent examples from own research are presented below.

ENERGY-EFFICIENT AND WATER-SAVING IRRIGATION METHODS

Surface irrigation techniques as predominantly applied in developing countries cause system-related deep percolation losses of 40%. In most cases, the losses are even higher. On the background of increasing water scarcity, water-saving irrigation methods are becoming more and more important. Micro-irrigation is one of the most efficient methods because it provides demand-oriented water supply to the root zone and thus minimizes losses due to seepage and unproductive evaporation.

Beside water also energy for water lifting is a limited resources in irrigation. Therefore, the development of water and energy saving irrigation systems is of high priority. On this background a photovoltaic (PV) driven low-pressure drip irrigation system has been developed and tested in a 1.7 ha mixed date/citrus-orchard in Inshas Science City, Egypt. The installed power of the PV generator was 530 W_p. To reduce investment, the system was working without high-level tank by direct feeding into a special designed low pressure drip irrigation setup. Total system efficiency was 3% at a PV generator efficiency of 7%. Efficiency could be increased by cleaning the PV array from air-born dust that accumulates rapidly. Choosing a generator inclination of 18°, the daily flow of the pump met exactly the summer water requirement of the orchard. During winter time, pump flow is in surplus and the pump is controlled via soil moisture sensors to prevent water losses by deep percolation [2, 3].

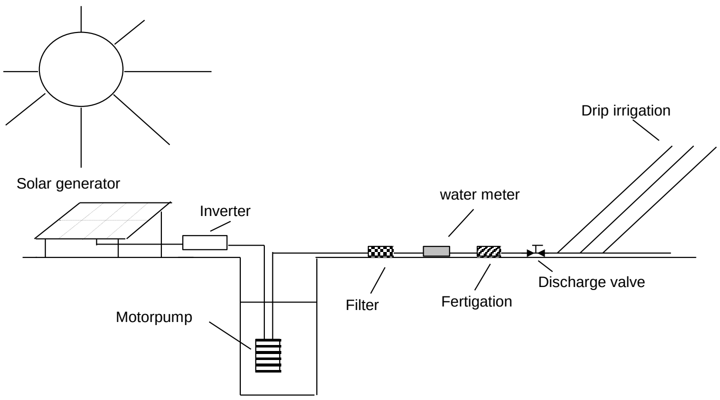

Figure. 2: Typical set-up of photovoltaic (PV) driven drip irrigation system

The expenses of PV irrigation systems are mainly governed by the number of required PV modules. Therefore, such systems should only be applied to energy-saving irrigation methods like drip irrigation (Fig. 2). Photovoltaic powered drip irrigation systems show self-controlling effects, because both, crop water requirement and flow of the pump are correlated to solar radiation. This effect is most visible for irrigating permanent crops in an arid climate, resulting in a high use of pump capacity and consequently in a high profitability [4].

In order to save more water, methods of deficit irrigation are being developed. Here, the plants are exposed to temporally and spatially defined drought stress in order to stimulate their natural adaptation mechanisms. A special form of deficit irrigation is partial root-zone drying (PRD), which means that the water is applied alternately to one half of the root zone in an interval of 10 to 14 days. The drying root system sends chemical signals to the canopy, which are not yet fully understood. However, abscisic acid (ABA) plays a major role in this system. ABA is transported by xylem flow to the leaves and reduces stomatal conductivity. Since photosynthesis is less reduced than transpiration, water use efficiency (WUE) is increased. In a cooperate research project in Thailand, we applied this method in mango. Even though irrigation quantity was reduced by 50%, yield decreased only slightly. Furthermore, results have shown that deficit irrigation did not impair the quality of the fruit with regard to colour, firmness, sugar/acid ratio, and sugar composition. The PRD variant even showed significant advantages with regard to fruit size distribution and the percentage of utilizable pulp [5, 6]. The payback period for the more sophisticated irrigation system was five years. If government would no longer provide water to the farm gate free of cost as it is done until now, the water savings would even result in a shorter pay-back period [7].

As surfaced irrigation is much more common, than sprinkler irrigation or micro-irrigation, we also applied PRD to tomato using a furrow irrigation system in Ethiopia. This irrigation technique is based on alternating wetting and drying of the opposite sides of the plant root system in subsequent irrigation events by watering one furrow and keeping dry the adjacent furrow until reversing in the next irrigation cycle. Therefore, the system is called alternate furrow irrigation (AFI). The results showed that marketable yield, numbers of fruits per plant and fruit size were not significantly affected by AFI. About 30% of irrigation water could be saved and WUE was increased by 37% [8, 9]. In accompanying greenhouse experiments with two tomato cultivars, namely Matina and Cochoro, it could be shown that PRD can enhance health-promoting qualities of tomato by increasing contents of vitamin C, lycopene, and β-carotene as well as antioxidant activity. However, the impact on vitamin C, lycopene and antioxidant activity was cultivar-dependent. The vitamin C and lycopene contents in Matina were enhanced, where-as the values were significantly decreased in Cochoro. Thus, it was shown that the choice of appropriate cultivars under different irrigation techniques is crucial for maintaining or modulating the quality and nutritional contents in tomato, while allowing for water savings [10].

Irrigation management with regard to the time and quantity of water supply is as important as the application technique. Soil moisture sensors, such as tensiometers, are proven aids for this purpose. However, suitable switching points must still be determined for different crops and cultivation conditions. Therefore, our research focused on innovative approaches to measure drought stress directly at the plant. The visualization of leaf temperature with the aid of a thermal camera proved to be a suitable technique for this purpose. In well-watered crops, the stomata are opened when the canopy is exposed to solar radiation and the leaf area is cooled through the dissipation of evaporation heat. This allows temperatures near the wet bulb temperature, which is several °C below ambient temperature.

Figure 3. Digital image (left) and thermographic image (right) of a mango tree canopy; paraffin covered leave is not transpiring and representing a dry surface

Fig. 3 shows a thermographic image of mango leaves, one of which was sealed with paraffin. This prevented evaporation, and the temperature was considerably higher than in untreated leaves. Under drought stress, transpiration is reduced, and leaf temperature increases with stomatal resistance. Wet and dry standard surfaces are placed in the image section as reference temperatures. According to drought stress level, canopy temperature T_{canopy} is closer to temperature of a dry surface T_{dry} (max) and a wet surface T_{wet} (min), which is expressed as crop water stress index (CWSI) [11-13]:

$$CWSI = \frac{T_{canopy} - T_{wet}}{T_{dry} - T_{wet}} \quad (1)$$

In a joint study with the CIMMYT in Mexico, we could show the suitability of thermal imaging for rapid phenotyping in plant breeding. Thermal images of the canopy of 92 [14] and later 300 [15] maize genotypes were acquired to monitor their tolerance to drought stress. Significantly lower canopy temperatures were found in well-watered genotypes compared with drought-stressed genotypes. Significant differences ($p < 0.001$) between genotypes under drought stress were detected using thermal images. Genotypes, better adapted to drought conditions, exhibited lower temperatures. Furthermore, a close correlation between CWSI and normalized difference vegetation index (NDVI) and SPAD values was obtained, showing that plant water status is also reflected in plant vigour. This method still requires further research and development to be applied in agricultural practice. However, the costs of thermal imaging cameras have recently fallen significantly and the application in irrigation control systems comes within reach.

SOLAR ENERGY FOR POSTHARVEST FOOD PROCESSING

Vegetable and fruits have a high market value in tropical countries and are an important source of income in agriculture. However, these products perish easily. Due to the difficult traffic conditions and the lack of cooling facilities, drying is a favourable kind of preservation in particular for fruits because it not only prolongs shelf life, but also reduces transport weight. The increase in value which results from processing to refined "convenience food" is even more important. In Thailand, for example, litchis and longan are now dried even though this fruits have a robust pericarp and could be transported easily. However, excess supply due to new plantations is currently leading to price slumps in Asia, and the production of dry fruits is a profitable alternative for rural producer cooperatives [16-19].

In developing countries, spreading the drying material in thin layers on mats, trays or paved grounds to expose it to sun and wind is still the most common drying method. Since the drying process is relatively slow, considerable losses occur. Furthermore, insect infestation, enzymatic reactions, microorganism growth, and mycotoxin production cause significant reduction of the product quality. Non-uniform and insufficient drying also leads to deterioration of the crop during storage. Serious drying problems occur especially in humid tropical regions where some crops have to be dried during rainy season. In order to ensure continuous food supply to the growing population and to enable the farmers to produce high quality products, the development of efficient drying methods is of urgent necessity.

A promising concept of forced convection type solar dryers represents the solar tunnel dryer that was developed at University of Hohenheim [20]. This tunnel dryer is intended for being used on small farms or farmer cooperatives. The solar tunnel dryer consists basically out of a plastic foil-covered flat plate solar air heater, a drying tunnel and small axial flow fans, Fig. 4.

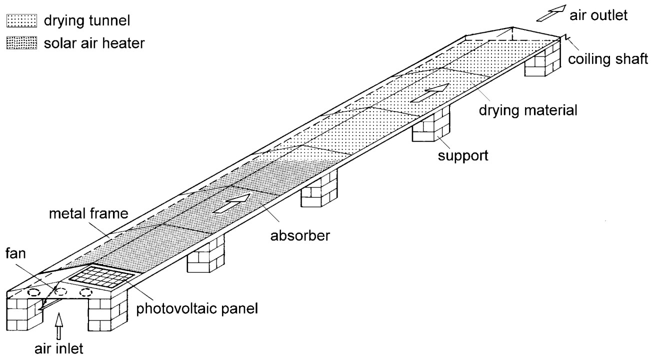

Figure 4. Solar tunnel dryer for direct solar drying with forced convection [20].

To simplify the construction and to reduce the production costs, the solar air heater is connected directly to the drying tunnel without additional air ducts. Both, the air heater and the drying tunnel are in-stalled on concrete block substructures to ease loading and unloading of the dryer. All parts of the dryer, including backside heat insulation and metal frames, are in modular design that facilitates transport and installation of the equipment.

The floor of the solar tunnel dryer consists of plastic foam sandwiched between two metal sheets with groove and tongue system. For dryers locally produced in developing countries, concrete or waterproofed plywood boards provided with heat and water resistant insulation material can be alternatively used as substructure and backside heat insulation. The insulator sheets are connected by a corrugated metal frame which also enables easy fixing and replacement of the transparent plastic cover foil by using reinforced plastic clamps. Solar air heater and dryer are covered with a transparent plastic foil. In a standard design using a 0.2 mm thick UV-stabilized PE foil useful life is 1 to 2 years before UV radiation and mechanical stress causes damage. On one length side of the dryer the plastic foil is fixed to the metal frame and on the other side, to a metal tube that allows coiling the foil for loading and unloading the dryer. To convert solar radiation into heat, the top surface of the absorber is painted black achieving an absorptance of about 90%. In humid tropical countries with frequent rain fall the covering sheet is tilted roof-like to prevent water entering the dryer. In arid regions a flat cover is sufficient. In the solar tunnel dryer the drying material is spread on a wire mesh placed 20 mm above the floor. Alternatively, trays can be used in order to ease loading and unloading. By this arrangement the drying material is exposed to the drying air from all sides.

Figure 5. Inflatable solar dryer (ISD) from outside (left) and inside (right)

Meanwhile, an inflatable solar dryer (ISD) was developed based on adaptations of the Hohenheim-type solar tunnel dryer (Fig. 5). To form a drying tunnel, transparent polyethylene (PE) film attaches by zipper to a reinforced black PVC film [21]. To reduce heat loss, a flexible multilayer floor was used along the drying area. The tunnel does not need a substructure as it is stabilized adequately from pressure created by two axial flow ventilators. During experiments, paddy was spread on the floor and mixed with a special roller bar. The ISD has been evaluated for paddy in the Philippines during rainy and dry seasons and was subsequently optimized. Moisture content was reduced from 23 to 14 % within 26 to 52 hours of continuous operation during the rainy season and 16 to 14 % within 4 to 26 hours of drying during the dry season. In both seasons, final moisture content of 12 % was reached after prolonged drying periods. The ISD showed advantages over sun drying, despite longer drying periods.

BIO-REFINERY APPROACH FOR RENEWABLE ENERGY PROVISION

As part of climate protection programs, the use of bioenergy is subsidized through governments of industrial countries. The import of bioenergy carriers from tropical countries, like palm oil from Malaysia and Indonesia, is leading to growing concerns regarding food security and resource protection in the countries of origin. This might be the reason why the interest in *Jatropha curcas* as a source of non-edible oil became very strong. As a basis for the development and optimization of equipment and techniques for the processing of the seeds, their physical properties must be known. For this purpose, thousand-grain mass, specific surface, bulk density, angle of repose, friction coefficient, and stress-strain behaviour were determined at University of Hohenheim University. In addition, a model for the correlation between seed mass and terminal velocity was developed, which can now be used for the pneumatic classification of the seeds [22]. Oil from *J. curcas* is mostly extracted with screw presses. For optimising extraction, the operating parameter settings were varied with regard to rotational speed, nozzle size, screw geometry, and press basket perforation in order to examine the effects on throughput, oil yield, and oil quality. The results showed that throughput and oil yield are negatively correlated and that the temperatures of the oil and the press cake increase with throughput and oil yield due to the growing mechanical load, which reduces quality [23]. After mechanical extraction, the oil still contains a large amount of suspended matter, which is separated through sedimentation [24]. Other components, such as phosphorus, calcium, and magnesium, as well as free fatty acids in aged vegetable oils, cause deposit formation during combustion processes. Since the determination of those components in the laboratory is relatively complicated, multiple linear regression analysis was used to correlate susceptibility to deposition with standard values of oil quality determination. The following limits were deduced as a recommendation for the avoidance of deposits during the combustion of jatropha oil: acid number below 6 mg KOH/g, water content below 0.15%, and ash content below 0.10% [25]. Due to its high protein content, the press cake would be of high nutritional value if not containing the toxic phorbol esters. Therefore, a detoxification technique was developed to produce protein concentrate from the press cake for animal nutrition. However, the seed shells are rich in fibre and should be removed prior to pressing. As no standard equipment is available, a hulling device for jatropha seeds was developed and optimized by discrete element method [26]. However, hulled seeds are not suitable for screw pressing because in absence of seed shells a dense pulp is forming and the oil hardly can be separated. A solution was found by co-extracting jatropha seed with grains like maize, rape seed or soybean that provide structure material and adding to the nutritional value at the same time. In terms of oil recovery and press cake quality, soybean appears to be the most suitable additive compared with rapeseed and maize [27]. Finally, by following bio-refinery approach, also a combustion device for the remaining jatropha shells was developed. Combustion for heat generation was enabled without previous processing of seed shell such as pelletizing or briquetting. Thermal power was between 11.1 and 36.7 kW corresponding to a feeding rate of shells between 2.9 and 9.0 kg/h with furnace efficiency of 87% and 91%. Ash melting and slag creation on the grate as well as clogging of the combustion air supply holes, by sintering ash on the grate was not observed. The concentrations of CO in the flue gas was below upper limit of 4 g/m3 for CO emission for combustion of wood according to German legal requirements for combustion units up to 50 kW. Coarse ashes are suitable for application as fertilizer in agriculture due to their high contents of the major plant nutrients [28]. However, attention has to be paid to the content of heavy metals, which has to be reduced by suitable methods.

CONCLUSIONS

Beyond the traditional role in providing safe food in adequate quantities under sustainable use of land and water, rural regions are key stakeholders in renewable energy provision. Use of solar energy and biomass are characterised by low areal density and, hence, are asking for decentral conversion. The complexity of the water-food-energy nexus does not encourage simple "one size fits all" solutions. Some recent developments can show exemplarily how the challenges of an earth system under stress might be answered by local approaches based on indigenous experience and knowledge enforced by state-of-the-art science.

REFERENCES

[1] Anonymous. International Energy Agency, Statistics Search; accessed 14.7.2017; available from: http://www.iea.org/.

[2] Müller, J., Schubert, M., Algohary, S., Hegazi, A., Köller, K. (1998). Performance of a photovoltaic drip irrigation system in Egypt. *Zeitschrift für Bewässerungswirtschaft*, 33(1), 5-20.

[3] Müller, J., Köller, K., Algohary, S., Hegazi, A. (1998). Solarbetriebene Tropfbewässerung in Ägypten. *Landtechnik*, 53(3), 138-9.

[4] Mayer, O., Müller, J. (1998). Alternative sources of energy - solar energy photovoltaic pumps and their use in irrigation systems. *Natural Resources and Development*, 47, 44-53.

[5] Spreer, W., Nagle, M., Neidhart, S., Carle, R., Ongprasert, S., Müller, J. (2007). Effect of regulated deficit irrigation and partial rootzone drying on the quality of mango fruits (*Mangifera indica*, L., cv. 'Chok Anan'). *Agricultural Water Management*, 88(1-3), 173-80.

[6] Spreer, W., Ongprasert, S., Hegele, M., Wünsche, J. N., Müller, J. (2009). Yield and fruit development in mango (*Mangiferea indica* L., cv. Chok Anan) under different irrigation regimes. *Agricultural Water Management*. 96(4), 574-84.

[7] Satienperakul, K., Manochai, P., Ongprasert, S., Spreer, W., Müller, J. (2009). Economic evaluation of different irrigation regimes in mango production in Northern Thailand. *Acta Horticulturae*, 831, 293-300.

[8] Bogale, A., Spreer, W., Gebeyehu, S., Aguila, M., Müller, J. (2016). Alternate furrow irrigation of four fresh-market tomato cultivars under semi-arid condition of Ethiopia – Part I: Effect on fruit yield and quality. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, 117(2), 255-68.

[9] Bogale, A., Spreer, W., Gebeyehu, S., Aguila, M., Müller, J. (2016). Alternate furrow irrigation of four fresh-market tomato cultivars under semi-arid condition of Ethiopia – Part II: Physiological response. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, 117(2), 269-82.

[10] Bogale, A., Nagle, M., Latif, S., Aguila, M., Müller, J. (2016). Regulated deficit irrigation and partial root-zone drying irrigation impact bioactive compounds and antioxidant activity in two select tomato cultivars. *Scientia Horticulturae*, 213, 115-24.

[11] Zia, S., Spohrer, K., Merkt, N., Wenyong, D., He, X., Müller, J. (2009). Non-invasive water status detection in grapevine (*Vitis vinifera* L.) by thermography. *International Journal of Agricultural and Biological Engineering*, 2(4), 46-54.

[12] Zia, S., Spohrer, K., Wenyong, D., Spreer, W., Romano, G., He, X., (2011). Monitoring physiological responses to water stress in two maize varieties by infrared thermography. *International Journal of Agricultural and Biological Engineering*, 4(3), 7-15.

[13] Zia, S., Wenyong, D., Spreer, W., Spohrer, K., Xiongkui, H., Müller, J. (2012). Assessing crop water stress of winter wheat by thermography under different irrigation regimes in North China Plain. *International Journal of Agricultural and Biological Engineering*, 5(3), 1-11.

[14] Romano, G., Zia, S., Spreer, W., Sanchez, C., Cairns, J., Araus, J. L., (2011). Use of thermography for high throughput phenotyping of tropical maize adaptation in water stress. *Computers and Electronics in Agriculture*, 79(1), 67-74.

[15] Zia, S., Romano, G., Spreer, W., Sanchez, C., Cairns, J., Araus, J. L., (2013). Infrared thermal imaging as a rapid tool for identifying water-stress tolerant maize genotypes of different phenology. *Journal of Agronomy and Crop Science*, 199, 75-84.

[16] Nagle, M., González Azcárraga, J. C., Mahayothee, B., Haewsungcharern, M., Janjai, S., Müller, J. (2010). Improved quality and energy performance of a fixed-bed longan dryer by thermodynamic modifications. *Journal of Food Engineering*, 99(3), 392-9.

[17] Nagle, M., González Azcárraga, J. C., Phupaichitkun, S., Mahayothee, B., Haewsungcharoen, M., Janjai, S., (2008). Effects of operating practices on performance of a fixed-bed convection dryer and product quality of longan. *International Journal of Food Science & Technology*, 43(11), 1979-87.

[18] Precoppe, M., Nagle, M., Mahayothee, B., Udomkun, P., Janjai, S., Müller, J. (2014). Optimal physicochemical properties of dried litchis for Thai consumers. *Int J Agric & Biol Eng*, 7(5), 103-10.

[19] Precoppe, M. F., Janjai, S., Mahayothee, B., Müller, J. (2013). Improved energy efficiency of farmers' cooperative litchi drying operation in Northern Thailand. International Journal of Food Science & Technology, 48(11), 2376-83.

[20] Müller, J., Mühlbauer, W. (2012). Solar drying. In: Tsotsas E, Mujumdar AS, editors. Modern Drying Technology Energy Savings. *Energy Savings. first ed. Weinheim (Germany), Wiley-VCH*, 4, 199-243.

[21] Salvatierra-Rojas, A., Nagle, M., Gummert, M., de Bruin, T., Müller, J. (2017). Development of an inflatable solar dryer for improved postharvest handling of paddy rice in humid climates. *International Journal of Agricultural and Biological Engineering*, 10(3), 269-82.

[22] Karaj, S., Müller, J. (2010). Determination of physical, mechanical and chemical properties of seeds and kernels of Jatropha curcas L. *Industrial Crops and Products*, 32(2), 129-38.

[23] Karaj, S., Müller, J. (2011). Optimizing mechanical oil extraction of *Jatropha curcas* L. seeds with respect to press capacity, oil recovery and energy efficiency. *Industrial Crops and Products*, 34(1), 1010-6.

[24] Karaj, S., Müller, J. (2014). Effect of container depth and sedimentation time on quality of Jatropha curcas L. *Oil Fuel*, 118, 206-13.

[25] Kratzeisen, M., Müller, J. (2010). Prediction of deposit formation during combustion of Jatropha oil from standard quality parameters. Fuel, 89(10), 2769-74.

[26] Romuli, S., Karaj, S., Müller, J. (2017). Discrete element method simulation of the hulling process of Jatropha curcas L. fruits. *Biosystems Engineering*, 155, 55-67.

[27] Romuli, S., Karaj, S., Latif, S., Müller, J. (2017). Performance of mechanical co-extraction of Jatropha curcas L. kernels with rapeseed, maize or soybean with regard to oil recovery, press capacity and product quality. *Industrial Crops and Products*, 104, 81-90.

[28] Kratzeisen, M., Müller, J. (2013). Suitability of Jatropha seed shells as fuel for small-scale combustion units. *Renewable Engery*, 51, 46-52.