Solar Energy and Post-Harvest Loss Reduction in Roots and Tubers in Africa

Kingsley O. Ukoba, *Member, IAENG*, Freddie L. Inambao, and Prudence Njiru

Abstract— **This study sheds light on the role affordable solar energy can play in the reduction of post-harvest loss in selected crops in Africa especially roots and tubers. The growing population places great strain on food supply chain, energy sources, and the environment. Roots and tubers are among the most consumed staple food in the continent of Africa. However, post-harvest losses threaten the crop and their products. The causes, processing and strategy for reducing post-harvest loss of roots and tubers are discussed. The state of solar energy and its possible contribution to the reduction of post-harvest loss of roots and tubers is also examined. The study concludes by proffering suggestions regarding the inclusion of solar energy as a way to reduce post-harvest losses in Africa.**

Index Terms— **Solar energy; post-harvest; roots and tubers; developing countries; Africa**

I. Introduction

The world population is estimated to reach 9.8 billion by 2050 [1]. This growing population means that 60 % more food is needed to sustain life on earth [2], [3], [4]. Reducing food losses, increasing production and improving distribution are vital for increasing food availability and access to all [5]. Globally, about 1.3 billion tons of food is lost annually according to United Nations estimates [6]. There are high losses at the post-harvest and processing stage in developing countries [7].

Food losses in developing countries especially South Asia and Africa are roughly 120 kgs/year to 170 kgs/year. In Uganda, an estimated US$23 million/year is lost caused by 27 % post-harvest loss of milk [8]. In South Africa food loss is estimated to be about 10 million tons every year which represent 210 kg per person per year [9]. This represents 33 % of the 31 million tons of food produced annually in South Africa. South African food losses consist of 44 % fruit and vegetables, 26 % grains, 15 % meat, and 13 % roots, tubers and oilseeds. The bulk of this loss occurs at the initial stage of the food supply chain. Post-harvest lost is 50 %, processing and packaging is 25 %, distribution and retail 20 % and 5 % lost at the consumer level.

Root and tuber crops are staple foods for many people in developing countries, and the people most dependent on them are the very poor who live in Asia and Africa [10]. Collectively, these crops occupy about 50 million ha worldwide and annual production exceeds 550 million tonnes, about two-thirds of which is harvested in the developing world. Roots and tubers provide food for 200 million people in Africa [11], [12]. They are farmed by peasant farmers because they have low labour requirements for cultivation [13].

II. Post-harvest Losses in Roots and Tubers

Cereals, roots, tubers and plantains constitute over two-thirds of the staple foods in the average sub-Saharan African diet in terms of energy [14]. Root and tuber crops are currently the second most important food crop category in several parts of Africa especially west Africa and Kenya, after cereals. The current longer and drier conditions in all agricultural areas, attributed to global warming, have led to a reduction in cereals production. It is estimated that the livelihoods of 70 % of Africans are dependent on rain-fed agriculture, an activity that is characterized by small-scale, subsistence farming that is vulnerable to a variety of stresses, including those associated with climate [15], [16]. Root and tuber crops are high yielding crops that can grow in diverse environments including arid and semi-arid lands (ASALs), thus providing a great potential for ensuring food security for the majority of Africans. In spite of the potential for these crops to address food security, a significant proportion of rural communities in Africans are constantly faced with food deficits.

Root and tuber crops are plants that store edible material in subterranean roots, corms or tubers and provide energy in the human diet in the form of carbohydrates. Cassava and sweet potatoes are root crops while potatoes, arrow root and yams are tubers. Roots, tubers and plantains are rich in highly digestible starch and provide more dietary energy per hectare than cereals. However, they are low in protein and other nutrients [17].

The main root and tuber crops produced in Africa are Irish potatoes, sweet potatoes, cassava, yams and cocoyam. It is estimated that in 2015, the area under Irish potatoes in Kenya was 147 780 ha which resulted in a production of 2.9 million tonnes valued at US$582 million. Similarly, the production of sweet potatoes was 967 879 tonnes from an area of 73 890 ha valued at US$310 million. In 2009, Kenya

Manuscript received May 24, 2018; revised July 19, 2018. This work was supported by the National Research Foundation and The World Academy of Science (NRF-TWAS) of South Africa under grant number 105492.

O. K. Ukoba is with the University of KwaZulu-Natal, 238 Mazisi Kunene Rd, Glenwood, Durban, 4041, South Africa (corresponding author: +27640827616 and +2348035431913; e-mail: ukobaking@yahoo.com and 216075239@stu.ukzn.ac.za).

F. L. Inambao is with the University of KwaZulu-Natal, 238 Mazisi Kunene Rd, Glenwood, Durban, 4041, South Africa (e-mail: inambaof@ukzn.ac.za).

P. Njiru is with the Kenya Industrial Research and Development Institute, Nairobi, Kenya (e-mail: prudence178@gmail.com)

produced 820 000 tonnes of cassava on 70 000 ha.

A. *Causes of Post-Harvest Losses*

The high moisture content of these crops means that they are bulky, highly perishable and costly to transport. Poor harvesting practices and post-harvest handling of roots and tuber crops are major causes of crop losses. The major practice is poor handling of harvesting tools which can cut the root/tuber leading to fungal contamination and deterioration especially when the harvest is not consumed or sold immediately. Moreover, farmers do not have access to equipment that could help them process more efficiently.

Root and tuber crops are a source of income for many poor households. Sweet potatoes and cassava particularly can grow under harsh climatic conditions and provide cash incomes to households that would not have had anything else to sell, hence the direct physical loss of the crop and postharvest deterioration causes a reduction in quality that results in price discounts and so contributes to economic losses [18], [19].

B. *Processing of Roots and Tubers*

Root and tuber crops are generally consumed in their fresh form in households, institutions and food service establishments. Their production and consumption are affected by the availability of other food crops as well as perception. The perception of cassava as a ‘poor person’s crop’ and the fear of cyanide poisoning has greatly affected its status as a staple food crop in the continent. Cases of death due to consumption of raw or inappropriately processed roots are frequently reported in the continent. It is unarguable that cassava contains cyanogenic glycosides which are converted to toxic hydrocyanic acid when the cells are ruptured. However, the cyanide content of the roots can be reduced to non-toxic levels if they are correctly processed. Hydrocyanic acid is a volatile compound that evaporates readily at temperatures above 28 °C and dissolves readily in water. This means that simple procedures such as shredding, pressing, washing, fermentation and drying can reduce the cyanide content to non-toxic levels.

The local machine manufacturers also need to be challenged to produce more advanced machines such as flash dryers, extruders, peeling machines, graters, chippers and hydraulic presses which are expensive to import. It has been shown that improvements in the processing sector, such as a shift to mechanical peeling, could help lower losses in the cassava value chain by about 44 % according to a recent study by [20].

C. *Strategy for Post-Harvest Loss Reduction*

The major strategy for reducing post-harvest loss in Africa is the behavioural approach. This involves the introduction of the farmers especially the peasant farmers to the concept of post-harvest loss and prevention techniques.

The greatest constraint to the processing of powders from the bulky roots and tubers is drying which may take up to 4 days to complete in sun drying. Long drying durations in the sun often leads to heavy microbial contamination. Conventional electric tray drying is fast but is inefficient and expensive because of the large amounts of water needing to be removed coupled with the high cost of energy. This can be ameliorated with an affordable, stable and sustainable power supply. Renewable energy is a viable solution to ending the global electricity problem as it exceeds world electricity demand [21]. Renewable energy comprises geothermal, solar, oceanic, wind, hydro, biomass and other energy sources. Solar energy can be converted to use direct current electricity using solar cells.

D. *Post-Harvest Loss Using Solar*

The loss of roots and tubers can be minimized by providing the right environment for storage and preservation.

Preservation

One of the major ways of preserving roots and tubers is by drying which involves moisture content reduction in the roots and tubers. This enhances the shelf life and eases transportation of the product. It also reduces the space needed for storage of the crops.

Root and tubers can be dried using open sun drying or/and solar dryers. Open drying can either be direct sun or shade drying. Open sun drying is common practice among subsistence farmers in Africa for preserving agricultural products, although this method encourages losses in quantity and quality of the dried crops. It also leads to contamination of the product due to exposure to dirt, and infestation from animals.

Electricity powered drying is a major solution to post-harvest loss reduction. It helps preserve the crop by drying and improves the quality of the dried product. However, the unstable and expensive nature of electricity in developing countries hampers usage of such dryers, especially by subsistence farmers. With alternate materials being researched for solar energy, it is possible for developing countries to be able to benefit from cheap and stable electricity generated from solar energy.

There are currently four classifications of solar dryer:

1) Sun or natural dryers: The root and tubers are placed directly under exposed conditions like solar radiation, ambient air temperature, relative humidity and wind speed to achieve drying. This tends to contaminate the dried product.
2) Direct solar dryers: the root and tubers are placed in an enclosure with transparent covers or side panels. Heat is generated by absorption of solar radiation on the product itself as well as the internal surfaces of the drying chamber. This heat evaporates the moisture from the drying product and promotes the natural circulation of drying air.
3) Indirect solar dryers: air is first heated in a solar air heater and then ducted to the drying chamber to dry the roots and tubers.
4) Mixed-type solar dryers: This uses the combined action of the solar radiation incident directly on the root and tubers and the air pre-heated in the solar air heater furnishes the energy required for the drying process.

ISBN: 978-988-14048-1-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

TABLE I
THE INSTALLED CAPACITY OF SOLAR PV TECHNOLOGY IN A TYPICAL AFRICA COUNTRY (NIGERIA)

S/n	Applications	Solar PV Capacity (%)
1.	Residential (mostly lighting)	6.9
2.	Rural electrification and Television	3.9
3.	Commercial lighting and equipment	3.1
4.	Street, Billboard and another lighting	1.2
5.	All lighting	15.1
6.	Industrial	0.4
7.	Health centre/clinic	8.7
8.	Telecom and radio	23.6
9.	Water pumping	52.2
	TOTAL	100

Storage

For products that are required in the fresh state, drying is not an option. Solar powered storehouses or silos are therefore designed to help preserve them in their harvested state. This requires a lot of electricity to keep the crop fresh for the duration required. A breakthrough in low-cost solar cells and panels will afford the peasant farmers access to such facilities at a reduced cost.

E. State of Solar PV in Africa

The Sub-Sahara Africa is home to about 85 % of the 1.3 billion people in developing countries without access to electricity [22] with an estimated electrification rate of 32 % [23]. About 70% Nigerians still uses unreliable energy sources [24] with 40 % connected to rationed supply from the national grid [25] and the rural populace mostly affected [26]. Electricity access has direct links to clean drinking water, good health and agricultural activities for rural dwellers [27], [28].

The lack of electricity has created, and is still responsible for, high levels of underdevelopment and poverty in rural areas [29], [30].

The major producers of roots and tubers experience the highest number of power outages per month with the longest duration of outage. Nigeria grid supply of electricity is on the average of 4 hours per day rationed among inhabitant in the city [31]. Nigeria experiences about 32.8 outages in a month with over 35 hours of outage [32].

About 80 % of Africa experience inefficient and ineffective electricity supply. Several Africa countries have below 500 kWh per person per year including countries where roots and tubers are produced [33]. These figures were compared with developed, emerging and other developing countries in Africa. Only two countries (South Africa and Libya) surpass 2 000 kWh per person per year in the whole of the continent. This has an attendant effect on all spheres of the economy of the continent including post-harvest loss.

The bulk of the continent's electricity is supplied by hydro, gas, coal, and diesel. Most of these sources are seasonal and have an adverse effect on the environment. The Zambia Electricity Supply Corporation Limited which metamorphosed into ZESCO Limited in May 1994 supplies 80 % of Zambia electricity using hydropower. Eskom (South Africa) has about 27 operational coal power plants, and produces about 40 % of the total electricity generated in Africa. In Gabon 1.2 GW is supplied by hydro, gas and heavy fuel-powered stations. Nigeria had a total installed electricity capacity of 8 457.6 MW (81 % of total) in early 2014. Thermal power plants (gas-fired plants) dominate the Nigerian power supply mix alongside hydro. Kenya relies on geothermal and hydro plants for electricity generation, although it is also investing currently in coal-fired plants. These sources are seasonal, being phased out due to their effect on the environment and high cost of maintenance. Also, geothermal energy for individual homes is rather expensive compared to other renewable energy. Exploration of geothermal energy causes the release of hazardous gases trapped underneath the earth.

Global prices of solar panels seem to be reduced in several parts of the world but are still high in Africa. This is due to several reasons but mainly due to lack of adequate solar panel production plants in different regions of the continent. The sun's power reaching the earth is typically about 1 000 W/m^2. The total amount of energy that the earth receives daily is 1 353 W/m^2 [34]. The sun is the most readily and widely available renewable energy source capable of meeting the energy needs of the whole world. It can provide more power than any fossil fuel on the planet [35].

A survey was conducted in the northern part of Nigeria to show the application distribution of solar photovoltaic (PV) technology [36]. It shows that domestic water pumping accounts for 57 %, domestic lighting and rural for 8 %, experimental room air conditioning for 1 %, rural clinic refrigeration of clinic items like vaccines and lighting of the clinic and surrounding for 24 %, and communications (TV and radio) for 10 %. This is tabulated in table 1, adapted from Iloeje, [37].

South Africa has the highest PV solar plant installed capacity in Africa. South Africa has a steady supply of electricity generated mainly from coal. Africa's five biggest solar market are northern countries (Morocco, Algeria 357 mW and Egypt 60 mW), South Africa 1147 mW and Ghana (275 MW) [38]. Morocco supplies about 650 000 local people with electricity from their installed 160 MW solar plants as at February 2016. Although, large-scale solar projects in Africa are found in the northern countries of the continent, the major root and tuber producers are in west and east Africa.

These regions lag behind in terms of installed solar capacity. Also, they are among the top countries with unstable and expensive power supply despites the huge potential abound for solar energy.

F. Challenges

The high cost of implementation of renewable energy technologies, particularly solar, is the major impediment militating against their widespread use [39]. The high cost is not unconnected to the fact that nearly all the parts are imported from overseas at a very high cost. Most of the personnel and technologies are sourced abroad [36]. The key challenges facing the successful deployment of solar energy technologies can be grouped into cost, policy, technical, people and environment. Some of the key challenges of solar energy in Africa are discussed below.

5) Cost: Cost plays a major role in the life of people and the success or failure of a technology. Africa is home to both rich and poor, living in rural and urban areas. The initial investment in the cost of solar energy infrastructure is a factor militating against penetration of solar energy in Africa. The lack of adequate funding for solar energy development poses a high risk to the success of solar energy in several countries of Africa.

6) Policy: Most African countries do not have an inclusive national renewable energy policy. Countries like Nigeria have never formulated a complete energy policy, although there are some sub-sectoral policies that have been formulated. Policy is pivotal for using energy efficiently and facilitating the development of solar energy. The nonexistence of suitable policy has, to a large extent, contributed to the lack of attention to solar energy.
7) Technical: Lack of technological capability is an issue in penetration of solar energy in Nigeria. The bulk of the technologies for solar energy are imported thereby increasing the high investment cost of solar energy.
8) Cultural and low level of public awareness: There is a generally low awareness of the economic and environmental benefit of using solar energy in the continent. Also, the cultural inclination in some parts of Africa contributes to the low usage of solar energy, especially in agricultural related activities. Thus, the public is not well-equipped to influence the government. The public needs to be educated so that it can exert influence and thereby enhance the development, application, dissemination and diffusion of renewable energy resources and technologies in the national energy market.

G. Windows of Opportunity for Solar and reduction of Post-Harvest Loss of Roots and Tubers

The continent boasts massive solar insolation with over 3 000 hours per year of sunshine and up to 3 600 hours in desert regions. This can be combined with more research on alternate materials (metal oxide thin films) and methods to help speed up penetration of solar energy for reduction of post-harvest loss. Spray pyrolysis (SPT) and chemical bath deposition (CBD) are two of the methods that can thrive in Africa [40]. SPT and CBD require little or no electricity to perform research in solar cells and solar energy in general. Further research into affordable, clean and efficient solar cells can result in more solar technology in the continent.

III. Conclusion

With the abundant sunlight in Africa, solar technology can help reduce the post-harvest loss experienced in the continent especially among the staple crops like roots and tubers. More investment and research/development is needed in the development of solar technology starting with solar cells and panels production. A reduction in the post-harvest loss will produce more food to feed the hungry, improve the standard of living, bring foreign direct investment and a host of other benefits.

Acknowledgment

This work was supported by the National Research Foundation and The World Academy of Science (NRF-TWAS) of South Africa under grant number 105492. EMDI, Akure; KIRDI, Nairobi and UKZN, Durban are also acknowledged for their support.

References

[1] K. B. Newbold, *Population Growth. The International Encyclopedia of Geography*. Hoboken, NJ: Wiley, 2017.
[2] N. Alexandratos, and J. Bruinsma, *World Agriculture Towards 2030/2050: the 2012 Revision*. Rome: FAO, 2012.
[3] J. Valentine, J. Clifton-Brown, A. Hastings, P. Robson, G. Allison, and P. Smith, “Food vs. fuel: the use of land for lignocellulosic ‘next generation’ energy crops that minimize competition with primary food production,” *Gcb Bioenergy*, vol. 4(1), pp. 1-19, 2012.
[4] A. Flammini, M. Puri, L. Pluschke, and O. Dubois, *Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for all Initiative*. Rome: FAO, 2017.
[5] R. Gills, J. Sharma, and T. Bhardwaj, “Achieving zero hunger through zero wastage: An overview of present scenario and future reflections,” *Indian Journal of Agricultural Sciences*, vol. 85(9), pp. 1127-1133, 2015.
[6] J. Olesen, A. Gustavsson, M. Svensson, H. U. Wittchen, and B. Jönsson, “The economic cost of brain disorders in Europe*,” European Journal of Neurology*, vol. 19(1), pp. 155-162, 2012.
[7] K. Venkat, “The climate change and economic impacts of food waste in the United States,” *International Journal on Food System Dynamics*, vol. 2(4), pp. 431-446, 2011.
[8] V. Kiaya, Post-Harvest Losses and Strategies to Reduce Them. Technical Paper on Postharvest Losses. New York: Action Contre la Faim (ACF), 2014.
[9] WWF (2017). Food loss and waste: facts and futures [Online]. WWF South Africa. Available: awsassets.wwf.org.za/downloads/WWF_Food_Loss_and_Waste_WEB.pdf
[10] J. Léon, “Origin, evolution, and dispersal of root and tuber crops,” in *Proc. of the 4th Symposium of the International Society for Tropical Root Crops*, Cali, Colombia, 1-7 August 1976, 1977.
[11] A. McPherson, and J-L. Jane, “Comparison of waxy potato with other root and tuber starches,” *Carbohydrate Polymers*, vol. 40(1), pp. 57-70, 1999.
[12] R. C. Ray, and P. S. Sivakumar, “Traditional and novel fermented foods and beverages from tropical root and tuber crops,” *International Journal of Food Science & Technology*, vol. 44(6), pp. 1073-1087, 2009.
[13] J. Alleman, S. M. Laurie, S. Thiart, and H. J. Vorster. Sustainable production of root and tuber crops (potato, sweet potato, indigenous potato. *South African Journal of Botany*, vol. 70(1), pp. 50-66, 2004.
[14] J. E. Wenham, “Postharvest deterioration of cassava: A biotechnology perspective,” Plant Production and Protection Paper FAO No 130. Rome: FAO, 1995.
[15] A. J., Challinor, T. R. Wheeler, P. Q. Craufurd, C. A. T. Ferro, and D. B. Stephenson, "Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures." *Agriculture, ecosystems & environment* 119, no. 1-2 (2007): 190-204.
[16] K., Anderson, and W.A. Masters, (Eds.). (2009). *Distortions to agricultural incentives in Africa*. World Bank Publications.
[17] Poquette, Nicole Marie. "Effect of Functional Starch in Brown Rice and Grain Sorghum on Plasma Glucose and Insulin Responses in Humans." (2013).
[18] D. Naziri, W. Quaye, B. Siwoku, S. Wanlapatit, V. P. Tu, and B. Bennett, “Not all those who wander are lost: A comparative analysis of postharvest losses in cassava value chains in Ghana, Nigeria, Thailand and Vietnam.” Paper submitted for the 14th Congress of the European Association of Agricultural Economists ‘Agri-food and Rural Innovations for Healthier Societies’, Ljubljana, Slovenia, 2014.
[19] A. Westby, *Cassava Utilization, Storage and Small-Scale Processing*. Natural Resources Institute, University of Greenwich, UK, 2002.

[20] M. Schuster, and M. Torero, Reducing food loss and waste. International Food Policy Research Institute (IFPRI), IFPRI book chapters. 2016:9780896295827-03.

[21] Ellabban, Omar, Haitham Abu-Rub, and Frede Blaabjerg. "Renewable energy resources: Current status, future prospects and their enabling technology." *Renewable and Sustainable Energy Reviews* 39 (2014): 748-764.

[22] K. Kaygusuz, "Energy for sustainable development: A case of developing countries," *Renewable and Sustainable Energy Reviews*, vol. 16(2): pp. 1116-1126, 2012.

[23] N. Scarlat, V. Motola, J. F. Dallemand, F. Monforti-Ferrario, and L. Mofor, "Evaluation of energy potential of municipal solid waste from African urban areas," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 1269-1286, 2015.

[24] C.O. Nwokocha, U.K. Okoro, and C.I. Usoh, "Photovoltaics in Nigeria–Awareness, attitude and expected benefit based on a qualitative survey across regions" *Renewable energy*, *116*, pp.176-182. 2018.

[25] A.S. Aliyu, J. O. Dada, and I. K. Adam, "Current status and future prospects of renewable energy in Nigeria" *Renewable and sustainable energy reviews*, *48*, pp.336-346, 2015.

[26] M. Bazilian, P. Nussbaumer, H. H. Rogner, A. Brew-Hammond, V. Foster, S. Pachauri, E. Williams, M. Howells, P. Niyongabo, L. Musaba, and B. O. Gallachóir, "Energy access scenarios to 2030 for the power sector in sub-Saharan Africa" *Utilities Policy*, *20*(1), pp.1-16, 2012.

[27] J. Zhang, "Environmental health in China: progress towards clean air and safe water," *The Lancet*, vol. 375(9720), pp. 1110-1119, 2010.

[28] T. S. Epstein, and D. Jezeph, "Development—there is another way: a rural-urban partnership development paradigm," *World Development*, vol. 29(8), pp. 1443-1454, 2001.

[29] M. Kanagawa, and T. Nakata, "Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries," *Energy Policy*, vol. 36(6), pp. 2016-2029, 2008.

[30] K. Kaygusuz, "Energy services and energy poverty for sustainable rural development," *Renewable and Sustainable Energy Reviews*, vol. 15(2), pp. 936-947, 2011.

[31] M. O. Oseni, "Power outages and the costs of unsupplied electricity: evidence from backup generation among firms in Africa," in *Proc. USAEE/IAEE Conference*, Austin Texas. 2012.

[32] IRENA, *Solar PV in Africa: Costs and Markets*, 2016.

[33] D. Rogers, "The electrification of Africa." *Global Construction Review*, 2014 from http://www.globalconstructionreview.com/markets/electrification8373 7367363636363636363636-africa/.

[34] E. Hoff, and M. Cheney, "The idea of low cost photovoltaic," *Energy Journal*, vol. 93, p. 17, 2000.

[35] I. Dincer, "Renewable energy and sustainable development: a crucial review," *Renewable and Sustainable Energy Reviews*, vol. 4(2), pp. 157-175, 2000.

[36] E. Bala, E., J. Ojosu, and I. Umar, "Government policies and programmes on the development of solar-PV Sub-sector in Nigeria," *Nigerian Journal of Renewable Energy*, vol. 8(1&2), pp. 1-6, 2000.

[37] O. Iloeje, "Renewable energy development in Nigeria: status & prospects," in *Proc. National workshop on energizing rural transformation in Nigeria: scaling up electricity access and renewable energy*, 2002.

[38] Statista, "Global new installed solar PV capacity from 2000 to 2016 (in megawatts)", 2018. Available online at https://www.statista.com/statistics/280200/global-new-installed-solar-pv-capacity/

[39] A. V. Bridgwater, "Renewable fuels and chemicals by thermal processing of biomass," *Chemical Engineering Journal*, vol. 91(2-3), pp. 87-102, 2003.

[40] K. O. Ukoba, F. L. Inambao, and A. C. Eloka-Eboka, "Fabrication of affordable and sustainable solar cells using NiO/TiO2 PN heterojunction," *International Journal of Photoenergy*, vol. 2018, pp 1-7, 2018.