Available online: http://journal.uir.ac.id/index.php/JEEE/index

Journal of Earth Energy Engineering

Publisher: Universitas Islam Riau (UIR) Press

Characterization of Voltage Generation Obtained from Water Droplets on a Taro Leaf (*Colocasia esculenta L*) Surface

Ena Marlina[1], Akhmad Faruq Alhikami[1*], Metty Trisna Negara[2], Sekar Rahima Sahwahita[3], Mochammad Basjir[1]

[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Islam Malang, Jl. MT. Haryono No. 193, Malang, Indonesia 65144

[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Samawa, Jl. Raya Bay Pass Sering Sumbawa Besar, Sumbawa, Indonesia 84316

[3]Department of Nanotechnology, Faculty of Advanced Technology and Multidiscipline, Universitas Airlangga, Jl. Airlangga No.4 - 6, Airlangga, Kampus C, Surabaya, Indonesia 60115

*Corresponding Author: alhikami@unisma.ac.id

Article History:

Received: May 23, 2023
Receive in Revised Form: May 31, 2023
Accepted: July 20, 2023

Keywords:

Voltage generation, taro leaf, water droplet, contact angles.

Abstract

Voltage generation was obtained using a water droplet characterization on a taro (*Colocasia esculenta L*) leaf surface. This method relies on the superhydrophobic effect from the contact angle between the water droplet and the taro leaf's surface allowing electron jumping and voltage generation. Water droplets were dropped on the top of taro leaf surface equipped with aluminum foil underneath as an electrode. The voltage was measured at various slope angles of 20°, 40° and 60° in a real-time basis. A digital camera was used to capture the droplet movement and characterization. It is found that the taro leaf has a surface morphology of nano-sized pointed pillars which created a superhydrophobic field. The energy generation was primarily obtained from the electron jump which was caused by the surface tension of the nano-stalagmite structure assisted by the minerals contained in the taro leaf surface. The results reported that the smaller the droplet radius (the smaller the droplet surface area), the greater the droplet surface tension and the greater the voltage generation. Furthermore, the highest voltage generation was obtained 321.2 mV at 20°-degree angle of slopes.

INTRODUCTION

The increase in electrical energy consumption is one of the world's energy concerns. Therefore, a new technology development in alternative energy is required to replace the consumption of fossil fuels (oil, coal, and natural gas) (Zakaria, 2021). Recently, many researchers have explored renewable energy sources to solve the issue of the country's electrical energy crisis. They have tried to create environmentally friendly energy sources (Helseth, 2017; Lee, 2015). In addition, the renewable energy sources (biomass, hydropower, geothermal, solar, wind, and marine power plants) have fulfilled 30% (Neo, 2021).

Currently, scientists are developing technology to imitate the works of nature. The hydrophobic nature of the leaves is a fascinating physical phenomenon that the leaves are fearing of water or water repellent such as taro, banana, pandan, sweet leaves, etc. (Kudin, 2008; Tandon, 2008; Yatsuzuka, 1994). The hydrophobic surfaces are characterized by measuring the contact angle that formed on the surface. The contact angle is formed between the droplet and the solid surface when the droplet is dropped. Moreover, various studies (Amirtharajah, 1998; Beeby, 2006; Kim, 2009; Priya, 2007) on harvesting piezoelectric energy based on mechanical vibration have been conducted, converting mechanical stress into voltage and electric current. (Chau, 2009) concluded that the surface roughness of the hydrophobic materials influenced in the contact angle development. The apparent contact angle increases for hydrophobic materials with increasing in surface roughness.

DOI: 10.25299/jeee.2023.12916
eISSN: 2540-9352 pISSN: 2301-8097

Journal of Earth Energy Engineering
Vol. 12 No. 2, October 2023, pp 50-57

In addition, Negara et al. (Negara, 2020), and Subagyo et al. (Subagyo, 2017) conducted a study to reveal the interaction between droplets and taro leaves. A waxy layer covered on the taro leaf's surface with a nano-stalagmite structure consisted of functional groups with several minerals. The superhydrophobic field is created by nano stalagmites of Primary and Secondary Amines and Amides (bends) which tend to repulse water droplets (Negara, 2020). (Neo, 2021) demonstrated a larger scale of water droplet energy harvesting by using an improved electrode from a single stapler pin. The stapler pin was positioned vertically on a hydrophobic surface device. A single water droplet could produce short circuit current of 1.759 μA. The maximum power output of 0.116 mW was generated from a 9 x9 cm^2 apparatus with an array of 4 x 4 electrodes (Neo, 2021).

Hao et al (Hao, 2021) constructed a piezoelectric substrate by integrating elastic film and a polyvinylidene fluoride beam. Results showed that higher peak voltage generation was obtained from a pizzoelectric substrate than typical cantilever and fixed-fixed structures from water droplet impact. The peak voltage was steadly decreased while the vibration frequency of the film was increased. An optimal design obtained from the theoretical modelling could produce higher peak stresses and energy harvesting. Moreover, the presented structure can be further utilized in a wider range such as the rain voltage generation technology.

The superhydrophobic concept is the supremacy point of this research. It uses natural materials from plants which is very environmentally friendliness. The taro leaf (*Colocasia esculenta L*) used in this study has a morphology of nano-pointed pillars that formed the superhydrophobic properties of the taro leaf surface. Those nano-pointed pillars were influence on the amount of voltage generation. The novelty of this study was related to a novel method of voltage generation using water droplet characterization on taro leaf surface. The superhydrophobic effect on the taro leaf's surface allows the droplet stress to generate the voltage. Moreover, this study completes the previous study (Negara, 2020) which tested the effect of droplet trajectory at higher slopes of 20°, 40° and 60° on the produced stress on the the taro leaf's surface.

MATERIAL AND METHODS

Properties Measurement

In this study, taro leaf is the main component for harvesting energy. Taro leaf is classified in the kingdom Plantae, with the division *Tracheophyte*, belonging to the class *Magnoliopsida*, in the order *Alismatales*, with the family *Arcae*, belonging to the genus *Colocasia Schott*, species *Colocasia esculenta (L) Schott* (Chakraborty, 2015; Govaerts, 2021). Figure 1 shows the results of the Scanning Electron Microscope (SEM) test of taro leaf (*Colocasia esculenta (L) Schott*) reproduced from author's previous study (Negara, 2020). As seen in Figure 1, wax layer on the surface of taro leaves (*Colocasia esculenta (L)*) was enlarged at 1000 times magnification and 50μm scale. On this scale, there were small circles in the form of clusters with a circle border on the outside. This form was found to be identical at each location observed.

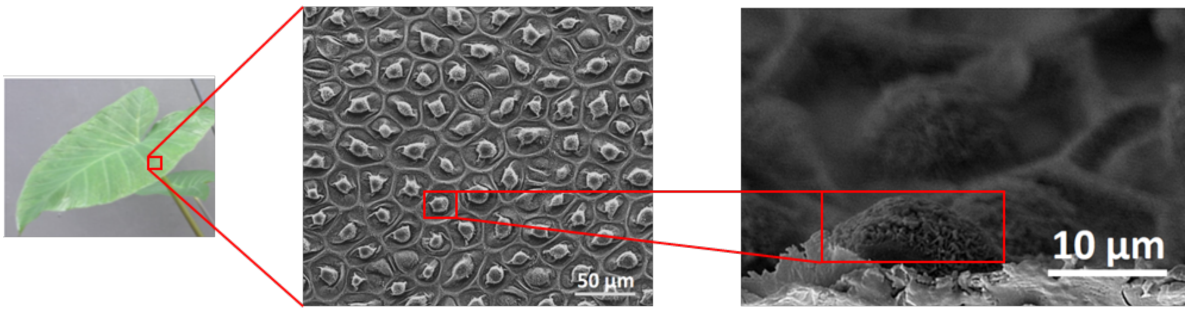


Figure 1. Images of SEM test reproduced from (Negara, 2020).

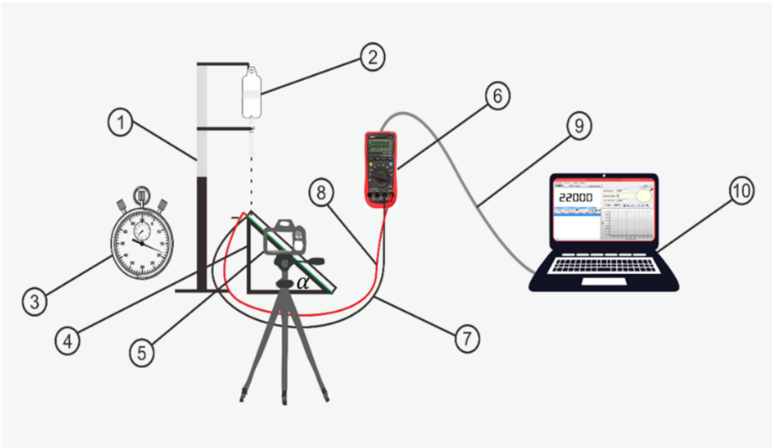
The chemical elements in taro leaves are Carbon (C), Nitrogen (N), Oxygen (O), Manganese (Mg), Clor (Cl), Potassium (K), and Calcium (Ca) (Negara, 2019; Negara, 2020; Subagyo, 2017). Despite their small content of Mg, Ca and K are reactive metal elements with good electrical conductivity, taro leaves were found to have a potential use for sustainable energy harvesting on a relatively small scale.

Table 1 lists of chemical components present in taro leaf (Negara et al., 2020).

Elements						
C	N	O	Mg	Cl	K	Ca
65.19%	7.40%	37.25%	1.25%	0.98%	9.62%	1.32%

Experimental apparatus

The research installation is shown in Figure 2. The superhydrophobic surface was prepared using taro leaves at 1 x 3 cm^2 surface area. Aluminum foil electrodes with a surface area of 1 x 3 cm^2 were mounted on the underside of the taro leaves. It was then connected to a multimeter to measure the voltage. The water tank was located at a higher position so that the water droplet dropped vertically on the surface of taro leaf. Once the water dropped at the surface, the electrons then jumped right after the droplet. After that, the droplet was in contact with the surface of the taro leaf. Finally, the electric voltage generated by a jumped electron when the droplet met the leaf's surface was recorded in a real-time basis using a data acquisition connecting to a monitor. Moreover, the water droplet images are captured using a Nikon D3300 camera. In this study, the voltages were measured at various slopes (α) of taro leaves of 20°, 40° and 60°.



1. Stand
2. Water tank
3. Stopwatch
4. Taro leaf's stand
5. A camera
6. A voltage meter.
7. Electric cable
8. Electric cable
9. Electric cable
10. A computer

Figure 2. Experimental setup

RESULTS AND DISCUSSION

The content of elements in taro leaves was Mg, K, and Ca (Mergedus, 2015). These elements play a role in the contact of water droplets on the top side of taro leaf in which those droplets do not flatten but roll off instead. These three elements efficiently reacted with water to generate hydrogen (H_2). The energy produced from the surface tension was enough to make all three elements react with water. The surface tension on the droplet equaled the surface force divided by the contact area between water droplets and the leaf's surface.

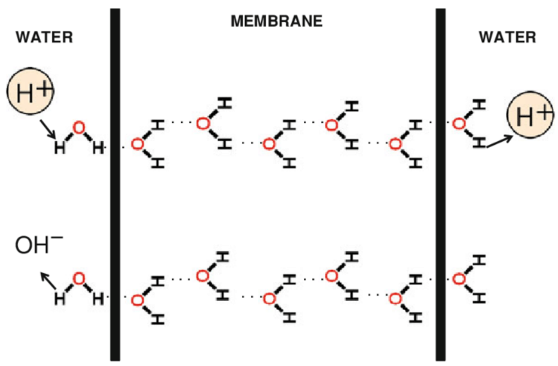


Figure 3. The mechanism of Grotthus (Li, 2021).

As shown in Figure 3, according to the Grotthuss Mechanism (Li, 2021), a water molecule consists of two Hydrogen atoms attached covalently to an Oxygen atom, but sometimes one H atom is hydrogen bonded.

Journal of Earth Energy Engineering
Vol. 12 No. 2, October 2023, pp 50-57

When the H atom formed a hydrogen bond with the nearby O atom, the H atom would ionize from the O atom into H+ ions. Moreover, the ionized H+ would be attracted by OH- ions nearby to form new H_2O. This phenomenon repeatedly continued in a single droplet. The Grotthuss mechanism would be more dynamic in the middle of a high surface when the taro leaf surface was in contact with H_2O droplets (Li, 2021; Maiyelvaganan, 2022). As a result, the droplet surface energy became very high. The effect caused the water surface on the taro leaves surface to have solid hydrogen bonds.

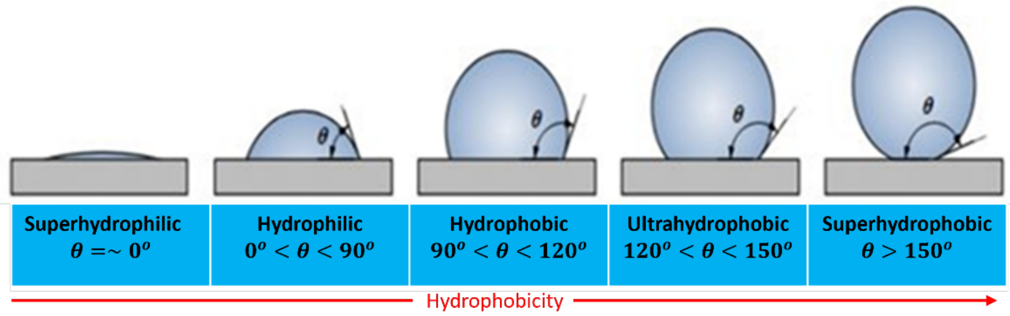


Figure 4. Illustration of of the angle of contact at different angle to the leaf surface

The contact angle is the angle formed from a surface line of the test object to a line. The level of hydrophobicity surface could be measured from the angle of contact with water droplets, as shown in Figure 4 above. At the contact angle $\theta < 30°$, the material's surface was hydrophilic, indicating that it liked water and was easy to contact with water. At the contact angle between $90° < \theta < 120°$, the surface of the material was already hydrophobic. At $120° < \theta < 150°$, it was over hydrophobic. Finally, at $\theta > 150°$, the material was superhydrophobic. Figure 5 shows the contact angle when the water droplet touched the leaf surface. Then, it rolled to the lower end of the surface with varying slopes at 20°, 40° and 60°. Moreover, when the droplet started moving towards the tip of the leaf surface, the droplet first touched the taro leaf surface to the end of the leaf surface. The interval was 6 seconds for 20°, 5 seconds for 40°, and 4 seconds for 60°.

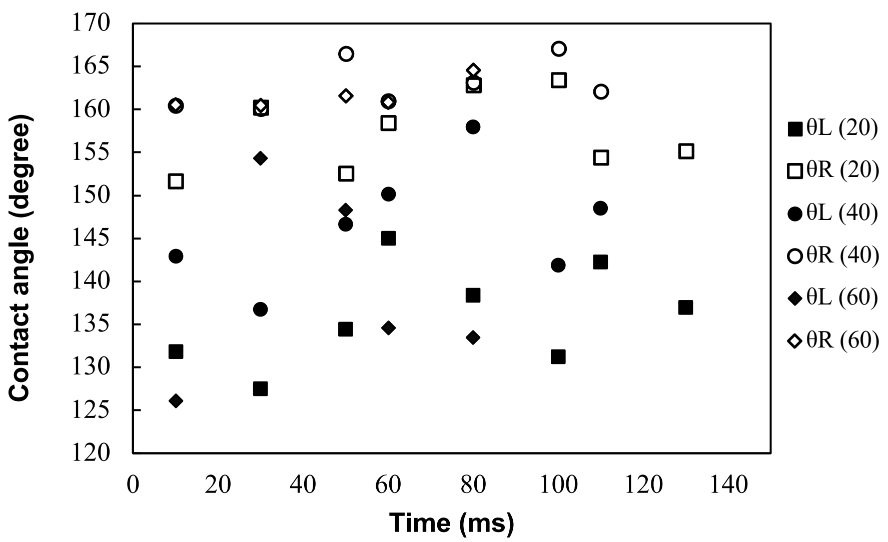
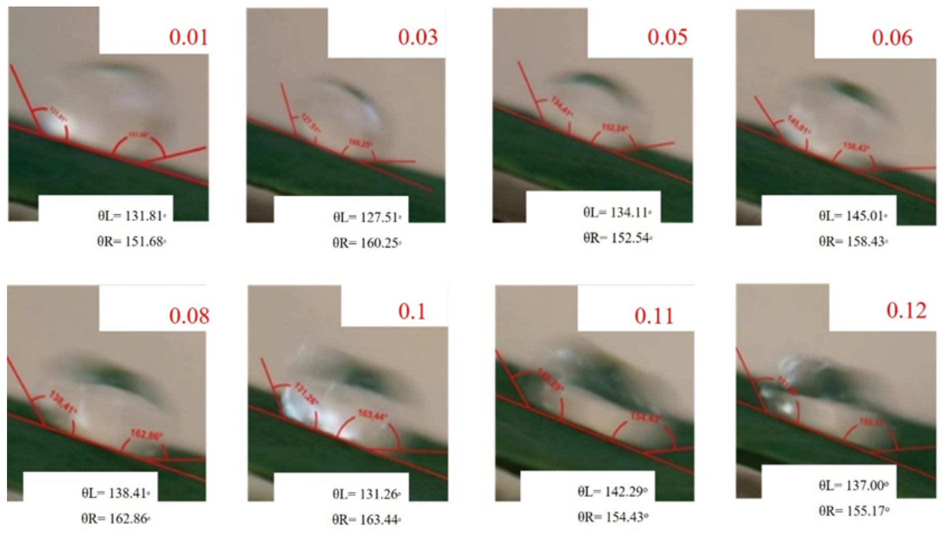


Figure 5. Contact angles with a slope of 20°, 40° and 60° on the left (θ_L) and right (θ_R) side contact angles.

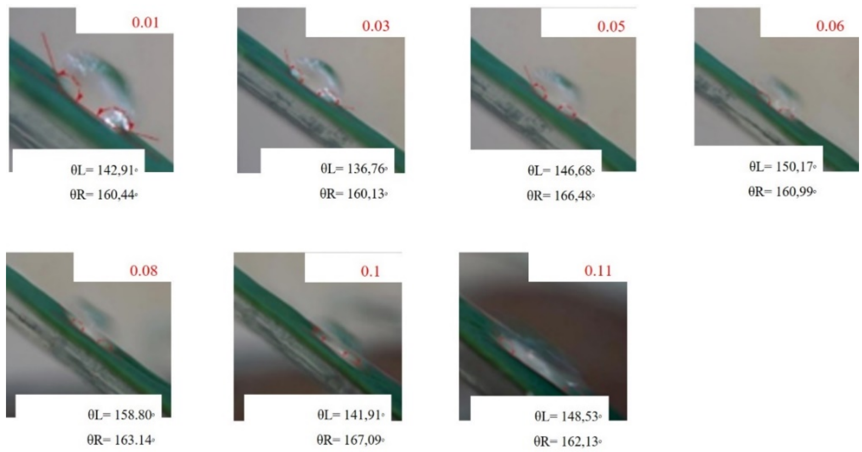
Taro leaves had a surface morphology of nano-sized pointed pillars and had a role in forming superhydrophobic properties (Negara, 2019). These nano-sized pointed pillars strengthened the hydrogen bonds between molecules when the droplets touched the surface of the taro leaves. These strong hydrogen bonds produced surface tension. The stronger the molecular bond, the greater the surface tension (Marlina, 2020). The force of the droplets was pushed away. This happened because the attractive forces between water molecules were getting stronger. The intermolecular forces of attraction at the droplet surface generate surface tension.

If the attractive force attracted hydrogen bonds between the water molecules in the large droplet and the length of the circular surface of the small droplet, hence the surface tension would be large according to the relationship of γ =F/L, where γ is a surface tension, F is the attractive force and L is the characteristic length, equivalent to contact-line length between droplet and surface.

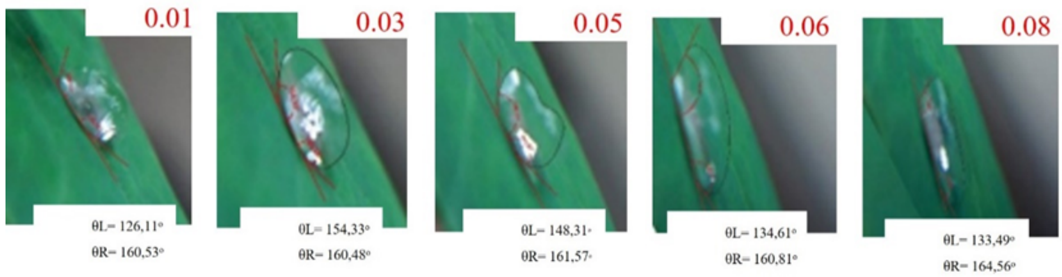
The surface tension was inversely proportional to the droplet surface area. It is noted that contact angle is time dependent as shown in Figure 5, even if it is superhydrophobic surfaces, the water droplets may percolate into surfaces or even vaporized, thereby, a small contact angle is observed. Also, the droplet size must be considerably small to avoid gravity effect. Moreover, the Bond number must be low (the balance between interfacial tension and gravitational forces) considering the previous works (Berry, 2015; Ridwan, 2020).



(a)



(b)



(c)

Figure 6. Contact angle on the left side (θ_L) and right side (θ_R) with (a) a slope of 20°, (b) a slope of 40°, and (c) a slope of 60°.

Journal of Earth Energy Engineering
Vol. 12 No. 2, October 2023, pp 50-57

Figures 6 visualizes the movement of droplets that formed the contact angle. The contact angle was the movement of droplets on the taro leaf's surface, with θ_L being the left contact angle and θ_R being the right contact angle using different droplet slope variations (20°, 40° dan 60°). The drops of water crossed the taro leaf's surface within 1 cm in width and 7cm in length. The initial position (X_0) was determined when the droplet initially touched the taro leaf's surface. Droplets that fall on the surface of the taro leaves rolled down due to the gravitational force and surface tension. When water droplets were on an inclined surface, the gravitational force pulled on the right side so that the surface tension on the right side increased (the contact angle value increased), while decreasing pressure on the left side reduced the stress.

As shown in Figure 6a, the maximum angle produced 20° slope at a 2 cm position was θ_L=145.01°, while θ_R = 163.44° was 4 cm. The maximum angle produced 40° slope at the 3 cm position was θ_L =158°, while θ_R =167.09° at the 4 cm position as seen in Figure 6b. Moreover, at a 60° slope, the maximum angle produced was θ_L =154.33°, the position was at 0.5 cm, and θ_R = 164.56° was at 5 cm as reported in Figure 6c.

Furthermore, the result showed that the droplet at the end of the track tended to be flat. The resulting angle between the taro leaf's surface and the droplet on the right side (θ_R) was around 150^0. The resulting angle proved that the taro leaf was superhydrophobic. The left side (θ_L) slope value was close to the right-side contact angle (θ_R). On the 20^0 track surface, the gravitational force pulled the right side (θ_R), so the surface tension increased. On the other hand, the pressure drop on the left side (θ_L) might reduce the surface tension. The reduction caused a larger right side contact angle (θ_R) compared to the left side (θ_L).

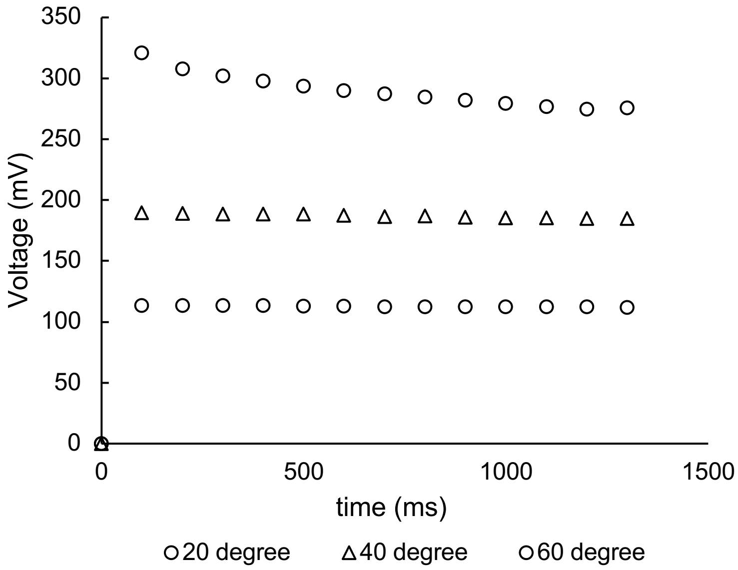


Figure 7. Voltage generation (mV) at various slope of 20°, 40°, and 60°

Figure 7 shows the voltage generation at different slopes angle of 20°, 40°, and 60°. It is worth noting that the voltage generation reported in Figure 7 can be represented as the surface stress of the water droplet molecule onto the taro leaf's surface. Due to surface tension, the water droplets never stay on the taro leaf surface. The surface tension diversely resulted in the droplet elasticity and motion. It is indicated that the greater the change, the greater the surface tension. Figure 7 showed that the 20° angle had the greatest stress because the droplets fell perfectly. Hence, the time for water droplets on the surface of the taro leaves was longer and caused the surface to increase. As shown in Figure 7, at the slopes of 40° and 60°, they had a faster time interval thus allowing the reduction of the surface tension and resulting in a lower voltage generation.

It is noted that the voltage production was created by surface tension which allowed the electron to jump (Negara, 2020). This occurred when surface exposure took place between functional groups on the taro leaf's surface (Mg, K, Ca, and H+) and OH- from H_2O water droplets. The driving mechanism was because of surface tensions and impulse forces of the reaction between the elements Mg, K, and Ca against OH-, H+ ions, and electrons as reported from (Negara, 2020). Mineral elements such as Mg, K, and Ca caused hydrogen to provide a strong push towards the droplets, where hydrogen was generated from the excitation of electrons. The voltage increased when the droplet contacted the leaf surface. Then, the droplet rolled down, oscillated, and disappeared from the surface. This process occurred at all angles of the slope as reported in Figure 7. It was found that the smaller the slope angle of the path, the greater the voltage generated. As a water droplet characteristic at the leaf surface, this could be elastically and repeatedly moved. In contrast, the change in shape could produce different surface tensions. The greater the elastic change in water droplets, the greater the surface tension. The added thrust caused the water droplet to roll over. Therefore, the water droplets oscillated and rolled down, resulting in the steeper the slope of the leaf surface, and the greater the angle of contact.

Figure 7 shows a graphic of the voltage production at real-time that produced by water droplets when in contact with the taro leaf surface at various slope angles of 20°, 40°, and 40°. When the droplet fell onto the taro leaf surface for the first time, the stress from the starting point of zero ($X = 0$) immediately increased. It was shown that a track with a slope of 20° produced a maximum voltage of 321.2 mV. A 189.6 mV were produced at the slope of 40°, and a 113.9 mV were produced at the slope of 60°. Moreover, the data indicated that the voltage generated by the 20° slope produced greater voltage than those of 40° and 60°. The contact angle (smaller radius) had a high surface tension hence, the surface energy of the droplet became larger. The smaller the droplet radius (the smaller the droplet surface area), the greater the droplet surface tension and the greater the energy contained on the leaf surface. The sudden increase in tension was caused by the droplet collision when it hit the leaf surface for the first time, causing very high surface tension and energy. The high energy was obtained due to the surface of the taro leaf, which has nano-sized stalagmites. The high energy was transformed into intense vibrations transmitted back to nearby water molecules. Moreover, Figure 7 showed that after the voltage increased, it immediately fell because the droplet jumped again. Hence, the contact angle decreased, resulting in slight surface tension, and generating less energy. Finally, the voltage trend showed a steady surface tension because the droplets were stationary and stable on the taro leaf's surface.

Figure 8 shows an illustration of the correlation between contact angle and surface tension that influence in the voltage generation. As shown in Figure 8, the increase in the contact angles has reduced the surface tension of the droplet. Hence, the voltage generation was found smaller. As seen in Figure 6, the contact angles between the droplet and the taro leaf's surface at the slope angles of 40° and 60° were relatively higher than those of 20°. Hence, the voltage generated by the 20° slope produced greater voltage than those of 40° and 60°.

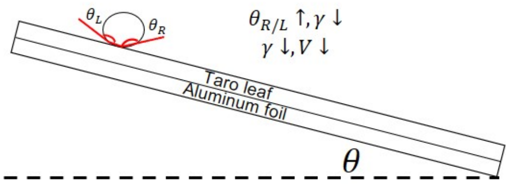


Figure 8. illustration of the relationship between contact angle and surface tension.

CONCLUSIONS

It is concluded that taro leaves have a surface morphology of nano-sized pointed pillars, which plays a potential role in forming superhydrophobic nature leading to an important role of producing higher surface tension and voltage generation. The angle between the taro leaf's surface and the droplet proved that the taro leaf is a leaf that has superhydrophobic nature. Furthermore, the maximum voltage generation was obtained of 321.2 mV at 20° slope angle allowing the droplet to slip perfectly. The time for the water droplets on the taro leaf's surface increased and caused the surface tension to rise. The smaller the droplet size led to the reduction in contact angles. Hence, the surface tension was greater which allowing to have higher voltage production.

Acknowledgment

The author shows gratitude to the Ministry of Research, Technology, and the Higher Education Ministry of the Republic of Indonesia for the provided grant for the research. Moreover, the research equipment was supported by the HI-MA Universitas Islam Malang and the Mechanical Laboratory of Brawijaya University

REFERENCES

Amirtharajah, R., & Chandrakasan, A. P. (1998). Self-powered signal processing using vibration-based power generation. *IEEE journal of solid-state circuits, 33*(5), 687-695.

Beeby, S. P., Tudor, M. J., & White, N. (2006). Energy harvesting vibration sources for microsystems applications. *Measurement Science and Technology, 17*(12), R175.

Berry, J. D., Neeson, M. J., Dagastine, R. R., Chan, D. Y. C., & Tabor, R. F. (2015). Measurement of surface and interfacial tension using pendant drop tensiometry. *Journal of Colloid and Interface Science, 454*, 226-237. doi: https://doi.org/10.1016/j.jcis.2015.05.012

Chakraborty, P., Deb, P., Chakraborty, S., Chatterjee, B., & Abraham, J. (2015). Cytotoxicity and antimicrobial activity of Colocasia esculenta. *J. Chem. Pharm. Res, 7*(12), 627-635.

Journal of Earth Energy Engineering
Vol. 12 No. 2, October 2023, pp 50-57

Chau, T., Bruckard, W., Koh, P., & Nguyen, A. (2009). A review of factors that affect contact angle and implications for flotation practice. *Advances in colloid and interface science, 150*(2), 106-115.

Govaerts, R., Nic Lughadha, E., Black, N., Turner, R., & Paton, A. (2021). The World Checklist of Vascular Plants, a continuously updated resource for exploring global plant diversity. *Scientific Data, 8*(1), 215.

Hao, G., Dong, X., & Li, Z. (2021). A novel piezoelectric structure for harvesting energy from water droplet: Theoretical and experimental studies. *Energy, 232*, 121071.

Helseth, L., & Wen, H. (2017). Visualisation of charge dynamics when water droplets move off a hydrophobic surface. *European Journal of Physics, 38*(5), 055804.

Kim, H.-U., Lee, W.-H., Dias, H. R., & Priya, S. (2009). Piezoelectric microgenerators-current status and challenges. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 56*(8), 1555-1568.

Kudin, K. N., & Car, R. (2008). Why are water– hydrophobic interfaces charged? *Journal of the American Chemical Society, 130*(12), 3915-3919.

Lee, Y. R., Shin, J. H., Park, I. S., Rhee, K., & Chung, S. K. (2015). Energy harvesting based on acoustically oscillating liquid droplets. *Sensors and Actuators A: Physical, 231*, 8-14.

Li, B., Wang, Y., Wang, J., Yong, X., & Zhang, J. (2021). Quasi-Grotthuss mechanism in a nonporous sulphate. *Journal of Energy Chemistry, 57*, 233-237.

Maiyelvaganan, K., Kamalakannan, S., Shanmugan, S., Prakash, M., Coudert, F.-X., & Hochlaf, M. (2022). Identification of a Grotthuss proton hopping mechanism at protonated polyhedral oligomeric silsesquioxane (POSS)–water interface. *Journal of Colloid and Interface Science, 605*, 701-709.

Marlina, E., Wijayanti, W., Yuliati, L., & Wardana, I. (2020). The role of pole and molecular geometry of fatty acids in vegetable oils droplet on ignition and boiling characteristics. *Renewable Energy, 145*, 596-603.

Mergedus, A., Kristl, J., Ivancic, A., Sober, A., Sustar, V., Krizan, T., & Lebot, V. (2015). Variation of mineral composition in different parts of taro (Colocasia esculenta) corms. *Food chemistry, 170*, 37-46.

Negara, K., Wardana, I., Widhiyanuriyawan, D., & Hamidi, N. (2019). *The role of the slope on taro leaf surface to produce electrical energy.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

Negara, K., Widhiyanuriyawan, D., Hamidi, N., & Wardana, I. (2020). The Dynamic Interaction of Water Droplet with Nano-Stalagmite Functional Groups of Taro Leaf Surface. *Journal of Southwest Jiaotong University, 55*(2).

Neo, R. G., & Khoo, B. C. (2021). Towards a larger scale energy harvesting from falling water droplets with an improved electrode configuration. *Applied Energy, 285*, 116428.

Priya, S. (2007). Advances in energy harvesting using low profile piezoelectric transducers. *Journal of electroceramics, 19*, 167-184.

Ridwan, M. G., Kamil, M. I., Sanmurjana, M., Dehgati, A. M., Permadi, P., Marhaendrajana, T., & Hakiki, F. (2020). Low salinity waterflooding: Surface roughening and pore size alteration implications. *Journal of Petroleum Science and Engineering, 195*, 107868. doi: https://doi.org/10.1016/j.petrol.2020.107868

Subagyo, R., Wardana, I., Widodo, A., & Siswanto, E. (2017). The mechanism of hydrogen bubble formation caused by the super hydrophobic characteristic of taro leaves. *International Review of Mechanical Engineering, 11*(2), 95-100.

Tandon, V., Bhagavatula, S. K., Nelson, W. C., & Kirby, B. J. (2008). Zeta potential and electroosmotic mobility in microfluidic devices fabricated from hydrophobic polymers: 1. The origins of charge. *Electrophoresis, 29*(5), 1092-1101.

Yatsuzuka, K., Mizuno, Y., & Asano, K. (1994). Electrification phenomena of pure water droplets dripping and sliding on a polymer surface. *Journal of electrostatics, 32*(2), 157-171.

Zakaria, Z., Kamarudin, S. K., Abd Wahid, K. A., & Hassan, S. H. A. (2021). The progress of fuel cell for malaysian residential consumption: Energy status and prospects to introduction as a renewable power generation system. *Renewable and Sustainable Energy Reviews, 144*, 110984.