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Analysis of Leaf Moisture of Chinese Mustard Green and Water Spinach using Single-Port Circular SRR Microwave Sensor for Post-Harvest in the Agriculture Industry

***Abstract**. An analysis of leaf moisture for chinese mustard green and water spinach using a microwave sensor is presented in this paper. The microwave sensor is based on a Circular Split Ring Resonator (SRR) with a single-port of the input feeder. The sensor operates at resonant frequencies in the range of 3 GHz to detect different levels of moisture content of the leaves. The Circular SRR was designed in a commercialized EM simulator and fabricated using Rogers RO4350B. The permittivity of the leaf was simulated to analyze the response of resonant frequency of the Circular SRR. Then the fabricated Circular SRR was used to measure the leaf moisture of these two vegetables based on the different resonant frequencies. Results showed that frequency changes were detected for both types of vegetable leaves when the leaf's moisture decreased gradually. With this analysis, this microwave sensor can be used for post-harvest quality control in the agriculture industry.*

***Streszczenie.** W artykule przedstawiono analizę wilgotności liści gorczycy chińskiej i szpinaku wodnego za pomocą czujnika mikrofalowego. Czujnik mikrofalowy oparty jest na okrągłym rezonatorze z dzielonym pierścieniem (SRR) z pojedynczym portem zasilacza wejściowego. Czujnik działa na częstotliwościach rezonansowych w zakresie 3 GHz, wykrywając różne poziomy wilgotności liści. Circular SRR został zaprojektowany w skomercjalizowanym symulatorze EM i wyprodukowany przy użyciu RO4350B Rogers. Symulowano przenikalność elektryczną skrzydła w celu analizy odpowiedzi częstotliwości rezonansowej Circular SRR. Następnie wyprodukowano Circular SRR do pomiaru wilgotności liści tych dwóch warzyw w oparciu o różne częstotliwości rezonansowe. Wyniki pokazały, że zmiany częstotliwości zostały wykryte dla obu rodzajów liści warzyw, gdy wilgotność liścia stopniowo spadała. Dzięki tej analizie ten czujnik mikrofalowy może być używany do kontroli jakości po zbiorach w przemyśle rolniczym. (**Analiza wilgotności liści gorczycy chińskiej i szpinaku wodnego przy użyciu jednoportowego okrągłego czujnika mikrofalowego SRR do stosowania po zbiorach w przemyśle rolniczym**)*

Keywords: microwave sensor, leaf moisture, split ring resonator, agriculture industry.
Słowa kluczowe: czujnik mikrofalowy, wilgotność liści, rezonator z dzielonym pierścieniem, przemysł rolniczy.

Introduction

Post-harvest quality control of vegetables is crucial to ensure food safety, decrease food loss, and provide consumers with high-quality produce [1, 2, 3]. Furthermore, the preservation of fruits and vegetables is interdisciplinary, and new technologies and innovations play an essential role in preserving the quality of fruits and vegetables after harvest [4, 5, 6].

Proper ventilation and maintaining proper relative humidity during storage are essential to maintaining the highest possible post-harvest quality [7, 8]. Thus the quality such as appearance, texture, flavour, and nutritional value can be maintained as high as possible as the fresh produce travels throughout the supply chain.

Popular leafy green vegetables that are frequently used in regional cuisine in Southeast Asian nations (such Malaysia, Singapore, and Thailand) include water spinach and chinese mustard greens. They are frequently offered for sale in wet markets, grocers, and food distributors. To retain the quality of the vegetables throughout the supply chain, it is crucial to consider the moisture content detection of the leaves, to monitor the freshness of the vegetables [9].

Therefore, this paper proposes the use of a Circular Split Ring Resonator (SRR) to monitor the leaf moisture of these two vegetables (water spinach and chinese mustard green). Generally, SRR is a type of metamaterial [10] that can be used in many circuit applications, such as microwave filters [11, 12], antennas [13, 14], metasurface [15], and sensors [16, 17].

A ring-shaped conductor with a gap and a split at one end makes up the SRR structure. In microwave sensor applications, changes in the electromagnetic field can be sensed by the SRR as a way to monitor/measure or identify any material. There are applications of SRR in microwave sensors such as sensors for biomedical [18, 19], microwave fluidic sensors for electrolyte concentration measurements [20, 21], and microwave sensors for non-destructive testing [22, 23].

From the literature, several microwave sensors were designed and proposed for moisture detection in agriculture industries such as highly sensitive differential soil moisture sensor (DSMS) using a microstrip line loaded with a triangular two-turn resonator (T2-SR) and complementary of the rectangular two-turn spiral resonator (CR2-SR) [24], soil moisture content detection using complementary split-ring resonator (CSSR) metamaterial topology that built under biodegradable dielectric substrate of polylactic acid [25] and microwave sensing of grain moisture content using free space traveling–standing wave attenuation method [26].

In the application of leaf moisture detection, there are several designs were proposed for this application such as microstrip SRR for pomegranate, pear trees, and hackberry leaves [27], grape leaf moisture detection using microwave aperture antennas covered with the plastic porous film [28], tea leaves moisture detection using coaxial monopole sensor [29] and Schefflera leaf moisture detection using microwave transmission and reflection of horn antenna [30].

Circular SRR Design

As shown in Fig. 1, it is the Circular SRR that was redesigned from [27]. The SRR is a single port feed line where it has a circular split ring at the center structure. The equivalent circuit of the SRR is shown in Fig. 2 where the inductance is introduced by the split ring and the capacitance by the gap between the SRR and the microstrip feed line. In addition, a strong electric field (E-field) region is located at the coupling between the split ring.

Thus, it can be used as a sensing hotspot to detect different levels of moisture content in any leaf.

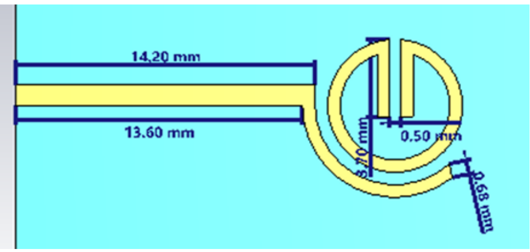


Fig.1. Dimension of single-port Circular SRR.

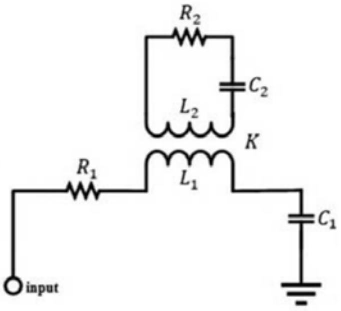


Fig.2. An equivalent circuit of single-port feed line SRR [27].

All the dimension values of the Circular SRR (Fig. 1) were determined based on the copper thickness of 0.0016 mm, substrate thickness of 0.51 mm, loss tangent tan, δ = 0.0007 and substrate dielectric constant, ε_r = 3.48. The substrate is Rogers RO4350B. The resonant frequency of the resonator is determined based on the dimension of the split ring structure.

Leaf Modelling in EM Simulator

As shown in Fig. 3, the leaf in EM simulator (CST Studio Suite) was modelled by adding a layer above the designed Circular SRR to act as a varying permittivity of the leaf. This is to observe the effect on the resonance of the Circular SRR.

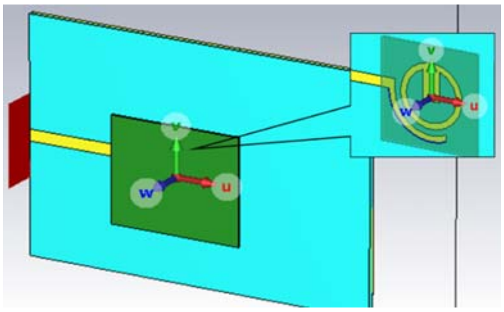


Fig.3. Leaf layer (green square) as a simulated leaf permittivity.

The leaf was modelled with a dimension of thickness of 0.2 mm, length of 10.5 mm, and height of 9 mm. To make the simulation more practical, a gap of 0.1 mm was placed between the leaf and the Circular SRR.

Fabricated Design and MUT Setup

The single-port Circular SRR as depicted in Fig. 4 is fabricated design through a fabrication process and measured using Vector Network Analyzer (VNA) for validation. At the feed line, this resonator has a length of around 2 cm. Therefore, a small size of the leaf is enough to be placed on the top of the Circular SRR structure. Two types of leaves as material under test (MUT) were measured which are chinese mustard green and water spinach. A small plastic clip was used to hold the leaf on the substrate during the drying process (using a heat blower) and also during measurement.

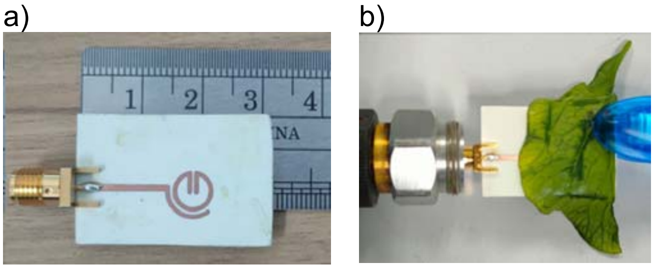


Fig.4. Photographs of (a) fabricated Circular SRR and (b) MUT (leaf).

Result and Discussion

Fig. 5 shows the simulated resonance frequency of the Circular SRR was at 3.81 GHz with S11 of -16 dB. Meanwhile, the measured resonance was at 3.77 GHz with S11 of -24.8 dB. By comparison, 40 MHz difference between the simulation and measurement; and the measurement of S11 is slightly higher than the simulation.

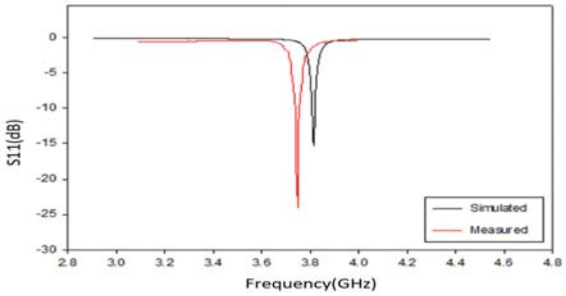


Fig. 5. Simulated and measured results of the resonance frequency of single-port Circular SRR.

Fig. 6 is the simulated frequency response shifting of the Circular SRR due to different permittivity of the leaf (as MUT). Four different permittivities were simulated in the software. In this graph, it was shown that the resonance of the Circular SRR was shifted to a lower frequency as the permittivity of the leaf increased. Thus, it can be said that as the leaf gets dried up, the permittivity decreases proportionally to the moisture loss in the leaf.

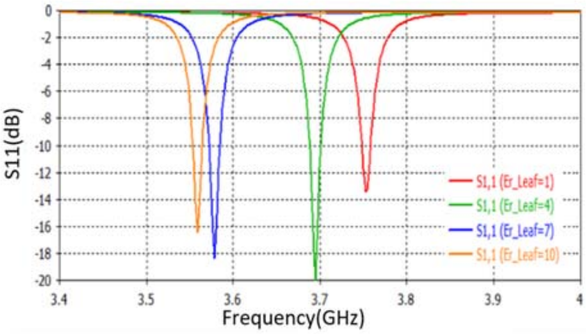


Fig. 6. Simulated frequency response shifting due to different permittivity of the leaf.

Fig. 7 and 8 are the measured S11 of the MUT of chinese mustard green and water spinach leaves respectively. The 0 hour is the initial resonance response without the drying process. A heat blower was used for heating the leaves for 30 seconds with an average temperature of 70 Cº. Then, the leaves were measured after 1 hour (1st measurement). This process was repeated for 2nd, 3rd and 4th measurements.

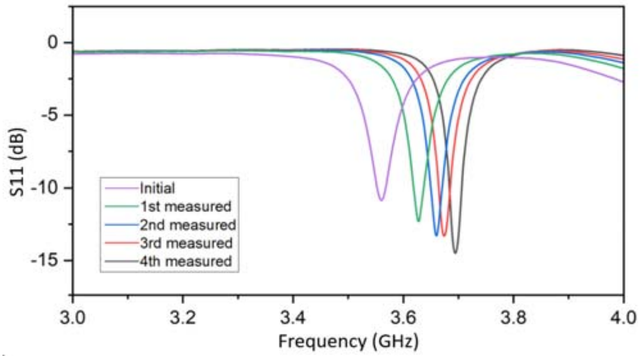


Fig. 7. The resonance response during drying the chinese mustard green leaf on the Circular SRR resonator.

It can be observed that for both chinese mustard green and water spinach leaves, the resonant frequency shifted to a higher frequency as the drying time increased for every 1 hour. Therefore, the leaf's permittivity is directly linked to its moisture content, so an increase in resonant frequency signifies a reduction in the leaf's moisture content. It can be concluded that the time it takes for drying is inversely related to the reduction of moisture content in the leaves.

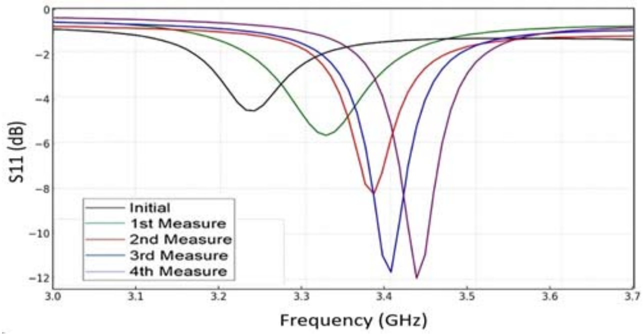
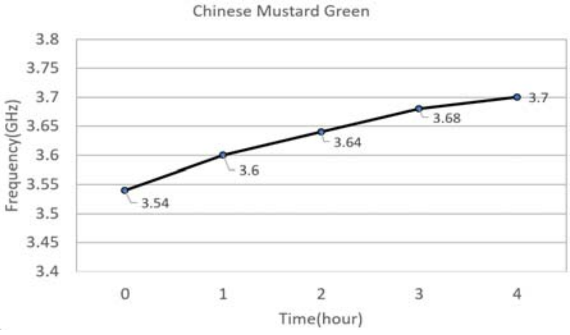


Fig. 8. The resonance response during drying the water spinach leaf on the Circular SRR resonator.

Fig. 9 is the detailed graph of resonant frequency versus measured time (for every 1 hour) for chinese mustard green (Fig. 9(a)) and water spinach (Fig. 9(b)). By comparing these two graphs, it can be seen that in the initial condition (0 hour), the water spinach leaf resonated a frequency lower than the chinese mustard green leaf which was 3.23 GHz as compared to 3.54 GHz. Besides, at 1 hour measurement (1st measure) the water spinach leaf dried faster as compared to the Chinese mustard green.

(a)



(b)

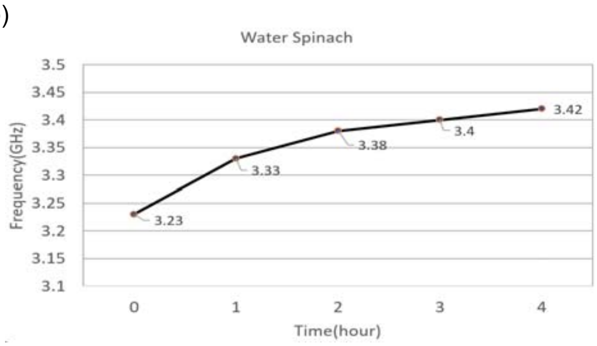


Fig. 9. Variation of resonant frequency during the drying process for (a) chinese mustard green and (b) water spinach.

Finally, in order to see the frequency variation of the resonance, Table 1 shows the percent (%) of the resonant frequency variation compared to the initial resonance (at 0 hour). The water spinach was higher than the chinese mustard green for the variation comparison of each hour. The frequency shift was higher for the water spinach leaf starting from 3.1% and gradually increasing to 5.9%.

Table 1. Resonant frequency variation compared to the initial resonance (at 0 hour).

Time (hour)	Chinese Mustard Green	Water Spinach
0 (initial)	0%	0%
1	1.7%	3.1%
2	2.8%	4.6%
3	4%	5.3%
4	4.5%	5.9%

Overall, the single-port Circular SRR can be used to measure or detect the moisture content of vegetable leaves for chinese mustard green and water spinach. The frequency shifting to a higher frequency is indicating that the leaf moisture has dropped. This can potentially be used as a microwave sensor for post-harvest quality control in the agriculture industry. For future works, a correlation needs to be made between the resonant frequency (f_0) and leaf moisture (%) in order to know how much the moisture content is for a certain period during the post-harvest of the vegetables.

Conclusion

A Circular Split Ring Resonator (SRR) with a single-port of the input feeder was designed and simulated in EM simulator. The resonator operates at resonant frequencies in the range of 3 GHz to detect different levels of leaf moisture of chinese mustard green and water spinach. The different permittivity of the leaf was simulated to analyze the response of resonant frequency of the Circular SRR. Thus, it can be said that as the leaf gets dried up, the permittivity decreases proportionally to the moisture loss in the leaf. Subsequently, the fabricated Circular SRR was employed to sense the moisture content of the leaves of the two vegetables by observing the resonant frequency changes. The findings revealed frequency variations in both types of vegetable leaves as their moisture levels decreased gradually. This microwave sensor, upon analysis, demonstrates its potential applicability for post-harvest quality control in the agriculture industry.

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REFERENCES

[1] Rajapaksha, L., D. M. C. C. Gunathilake, S. M. Pathirana, and T. Fernando. "Reducing post-harvest losses in fruits and vegetables for ensuring food security—Case of Sri Lanka." MOJ Food Process Technols 9, no. 1 (2021): 7-16.
[2] El-Ramady, Hassan R., Éva Domokos-Szabolcsy, Neama A. Abdalla, Hussein S. Taha, and Miklós Fári. "Postharvest management of fruits and vegetables storage." *Sustainable Agriculture Reviews*: Volume 15 (2015): 65-152.
[3] Workineh, Melkamu, and Hewan Lemma. "Post Harvest Loss Management and Quality Control of Fruits and Vegetables in Ethiopia for Securing Food and nutrition—A review." Food Sci. Qual. Manag 100 (2020): 21-28.
[4] Florkowski, Wojciech J., Nigel H. Banks, Robert L. Shewfelt, and Stanley E. Prussia, eds. Postharvest handling: a systems approach. Academic press, 2021.
[5] Aggarwal, Deepak, Robert L. Shewfelt, and Stanley E. Prussia. "Systems approaches for postharvest handling of fresh produce." In *Postharvest Handling*, pp. 17-49. Academic Press, 2022.
[6] Sugri, Issah, Mutari Abubakari, Robert Kwasi Owusu, and John Kamburi Bidzakin. "Postharvest losses and mitigating technologies: evidence from Upper East Region of Ghana." Sustainable Futures 3 (2021): 100048.
[7] Zainalabidin, Fazly Ann, Mozhiarhasi Sandra Sagrin, Wan Nabilah Wan Azmi, and Ainun Sabihah Ghazali. "Optimum postharvest handling-effect of temperature on quality and shelf life of tropical fruits and vegetables." Journal of Tropical Resources and Sustainable Science (JTRSS) 7, no. 1 (2019): 23-30.
[8] Lufu, Robert, Alemayehu Ambaw, and Umezuruike Linus Opara. "Water loss of fresh fruit: Influencing pre-harvest, harvest and postharvest factors." Scientia Horticulturae 272 (2020): 109519.
[9] Bandal, Amol, and Mythili Thirugnanam. "Quality measurements of fruits and vegetables using sensor network." In Proceedings of the 3rd International Symposium on Big Data and Cloud Computing Challenges (ISBCC–16'), pp. 121-130. Springer International Publishing, 2016.
[10] Rosaline, S. Imaculate, and S. Raghavan. "Exploring split ring resonators for GHz applications." In 2016 IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT), pp. 559-562. IEEE, 2016.
[11] M. Aldrigo et al., "Fast Method for the Assessment of SRR or ELC-Based Planar Filters: Numerical Analysis and Experiments," in IEEE Access, vol. 11, pp. 77307-77323, 2023.
[12] Qiao, Zhijun, Xuchao Pan, Fan Zhang, and Jianchun Xu. "A tunable dual-band metamaterial filter based on the coupling between two crossed SRRs." IEEE Photonics Journal 13, no. 3 (2021): 1-7.
[13] Keriee, Hussam *et al.,* "Wideband Planar Microstrip Antenna Based on Split Ring Resonator For 5G Mobile Applications." Przeglad Elektrotechniczny 97, no. 11 (2021).
[14] Sehgal, Puneet, and Kamlesh Patel. "Dual-Band Hexagonal SRR Antennas and Their Applications in SIMO and MISO-Based WLAN/WiMAX Systems." Progress In Electromagnetics Research B 99, no. 2 (2023).
[15] Budnarowska, Magdalena, and Jerzy Mizeraczyk. "Oddziaływanie płaskiej fali elektromagnetycznej z metapowierzchnią złożoną z rezonatorów SRR 2.5 GHz." Przegląd Elektrotechniczny 97, no. 2 (2021): 39-42.
[16] M. A. U. Haq, A. Armghan, K. Aliqab and M. Alsharari, "A Review of Contemporary Microwave Antenna Sensors: Designs, Fabrication Techniques, and Potential Application," in IEEE Access, vol. 11, pp. 40064-40074, 2023.
[17] A. Shah, O. Niksan, M. C. Jain, K. Colegrave, M. Wagih and M. H. Zarifi, "Microwaves See Thin Ice: A Review of Ice and Snow Sensing Using Microwave Techniques," in IEEE Microwave Magazine, vol. 24, no. 10, pp. 24-39, Oct. 2023.
[18] Ho, Yun-Rei, and Chin-Lung Yang. "A wearable throat vibration microwave sensor based on split-ring resonator for harmonics detection." In 2020 IEEE/MTT-S International Microwave Symposium (IMS), pp. 504-507. IEEE, 2020.
[19] Redzwan, Syaiful *et al.,* "Frequency domain analysis of hip fracture using microwave Split Ring Resonator sensor on phantom model." In 2016 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE), pp. 244-247. IEEE, 2016.
[20] Velez, Paris *et al.*, "Split ring resonator-based microwave fluidic sensors for electrolyte concentration measurements." IEEE Sensors Journal 19, no. 7 (2018): 2562-2569.
[21] Vélez, Paris, Jonathan Muñoz-Enano, and Ferran Martín. "Electrolyte concentration measurements in DI water with 0.125 g/L resolution by means of CSRR-based structures." In 2019 49th European Microwave Conference (EuMC), pp. 340-343. IEEE, 2019.
[22] Mukherjee, Saptarshi, Xiaodong Shi, Lalita Udpa, Satish Udpa, Yiming Deng, and Premjeet Chahal. "Design of a split-ring resonator sensor for near-field microwave imaging." IEEE Sensors Journal 18, no. 17 (2018): 7066-7076.
[23] Chauhan, Harish Kumar, Nilesh Kumar Tiwari, and Surya Prakash Singh. "Improved complementary split-ring resonator for nondestructive testing of materials." In 2017 4th IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics (UPCON), pp. 370-375. IEEE, 2017.
[24] Keshavarz, Rasool, Justin Lipman, Dominique MM-P. Schreurs, and Negin Shariati. "Highly sensitive differential microwave sensor for soil moisture measurement." IEEE Sensors Journal 21, no. 24 (2021): 27458-27464.
[25] Silva, Lincoln Alexandre Paz, Francisco de Assis Brito-Filho, and Humberto Dionísio de Andrade. "Analysis of metamaterial-inspired soil moisture microwave sensor." Microwave and Optical Technology Letters 64, no. 3 (2022): 422-427.
[26] Li, Chenxiao, Xiaoting Yu, Zezhao Chen, Qian Song, and Yanlei Xu. "Free space traveling–standing wave attenuation method for microwave sensing of grain moisture content." Measurement and Control 54, no. 3-4 (2021): 336-345.
[27] Yan, YuHeng, XianQi Lin, Zhe Chen, Yang Cai, and Zhi Chen. "A Microwave Sensor for Leaf Moisture Detection Based on Split-Ring Resonator." In 2020 IEEE Asia-Pacific Microwave Conference (APMC), pp. 427-429. IEEE, 2020.
[28] Pievanelli, Elisa, Riccardo Stefanelli, and Daniele Trinchero. "Microwave-based leaf wetness detection in agricultural wireless sensor networks." In 2016 IEEE Sensors Applications Symposium (SAS), pp. 1-4. IEEE, 2016.
[29] Ling, J. A., Y. L. Then, K. Y. You, J. Ahmed, and D. N. A. Zaidel. "Tea leaves moisture prediction using one-port monopole sensor." In 2017 IEEE Asia Pacific Microwave Conference (APMC), pp. 654-657. IEEE, 2017.
[30] Sinha, Kushagra, Olutosin C. Fawole, and Massood Tabib-Azar. "Non-invasive monitoring of electrical parameters of Schefflera arboricola leaf." In 2015 IEEE Sensors, pp. 1-4. IEEE, 2015.