Enabling high-quality compost for a smart domestic production

(Article begins on next page)

Enabling High-Quality Compost for a Smart Domestic Production

1st Giovanna Turvani
Dept. of Elec. and Telecomm.
Politecnico di Torino
Torino, Corso Duca degli Abruzzi 24
giovanna.turvani@polito.it

2nd Melania Fiore
Dept. of Applied Science and Technology
Politecnico di Torino
Torino, Corso Duca degli Abruzzi 24
melania.fiore@polito.it

3rd David O. Rodriguez-Duarte
Dept. of Elec. and Telecomm.
Politecnico di Torino
Torino, Corso Duca degli Abruzzi 24
david.rodriguez@polito.it

4th Francesca Demichelis
Dept. of Applied Science and Technology
Politecnico di Torino
Torino, Corso Duca degli Abruzzi 24
francesca.demichelis@polito.it

5th Tonia Tommasi
Dept. of Applied Science and Technology
Politecnico di Torino
Torino, Corso Duca degli Abruzzi 24
tornia.tommasi@polito.it

6th Francesca Vipiana
Dept. of Elec. and Telecomm.
Politecnico di Torino
Torino, Corso Duca degli Abruzzi 24
francesca.vipiana@polito.it

7th Fabrizio Riente
Dept. of Elec. and Telecomm.
Politecnico di Torino
Torino, Corso Duca degli Abruzzi 24
fabrizio.riente@polito.it

***Abstract*—Compost home production is an open challenge due to the need for continuous human intervention to monitor and regulate the critical parameters that play a fundamental role in the production of high-quality compost. The temperature and humidity require fine and uniform control over the entire mass to ensure a proper composting process development. This article presents a new prototype of a domestic smart composter that guarantees optimal control of the compost maturation process. This result is made possible by combining the ad-hoc design of a multi-sensor electronic board and microwave imaging techniques which provide a dual function: they allow both to control and monitor temperatures uniformly over the entire biomass.**

***Index Terms*—compost processing, multi-sensor electronic board, microwave sensing**

I. Introduction

Over the years, the techniques to obtain better quality fertilizer materials have been refined to nourish the soil by naturally eliminating the presence of insects and parasites [1].

Compost is one of the leading organic amendments used for sustainable agricultural practices. Organic amendments derive from biomasses and are rich in organic matter and nutrients. Thus they increase soil fertility and improve conditions for plant growth [2]. In these products, organic matter is stabilized and sanitized through specific processes. Composting is the process enabling the production of compost, a humus-like product made of fine particles, in which the original identity of the matrix cannot be distinguished anymore. Composting is a well-known process that occurs spontaneously in nature. Due to the long time required and the heterogeneous modalities of the natural process, composting has been improved over time to become a shorter and more controlled treatment that takes place in dedicated plants.

Composting takes advantage of aerobic microorganisms to transform and stabilize organic matter, usually provided in the solid state. The process is esoergonic, meaning that energy is released. This energy is in part used by microorganisms and in part lost as heat, leading to a temperature increase of the treated mass [3].

In the composting process, it is possible to identify different phases. The first phase is mesophilic, and the decomposition of easily degradable organic matter occurs during it. The decomposition of this matter is rapid and releases a large amount of thermal energy, which increases the mass temperature and the degradation rates, leading to the thermophilic phase. During this second phase, the temperature spontaneously reaches and exceeds 70 °C. Such a high temperature ensures the reduction of pathogenic agents in the treated material, allowing the stabilization and sanitization required. In controlled composting, this phase is limited in time and temperature. Finally, the third phase occurs. It is known as maturation and involves mineralizing hardly degradable molecules and humifying lignocellulosic moieties while the

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.
This study is also part of a PON PhD, funded by European Union FSE REACT-EU (PON Ricerca e Innovazione 2014-2020 - Asse IV, Azione IV.5 - Dottorati su tematiche green - DM 1061/2021)

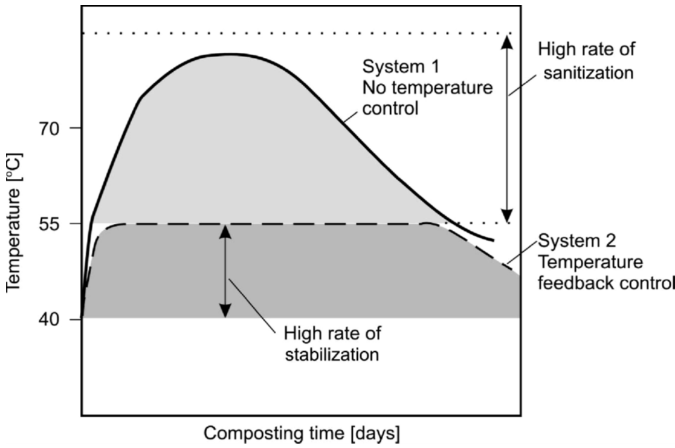

Fig. 1. Typical temperature vs time profiles for two composting systems: without (System 1) and with (System 2) temperature control, taken from [3].

temperature decreases. Therefore, the temperature is a valuable parameter for monitoring the progress of the process. Fig. 1 shows the typical temperature trend for two different cases, with or without temperature control.

The final processes are slower than the ones of the former phases, so the maturation phase usually lasts some weeks, depending on the composition of the treated material. Compost is ready to be used at the end of this final phase.

In addition to temperature and oxygen availability, other critical factors for the composting process are moisture content and nutrient availability, which depend primarily on the type of material that undergoes treatment. However, it can still be modified and regulated to a certain extent, by properly mixing different feedstock materials or by treating conveniently the matrix, i.e., by drying or by adding water, depending on the situation.

Composting sites are usually designed to treat large volumes of material at a time, ensuring the process runs smoothly and more rapidly than the natural one. Up to present time, there is a limited number of papers that face “small-scale” composting, but still this so called “small-scale” composting often deals with relatively huge volumes, from 100 to 400 liters, able to keep from 50 to 100 kg of raw materials [4] [5] . However, sometimes it is possible to work only with even smaller quantities, of just few kilos, and in these cases volumes smaller than 10 liters are used. Very few studies can be found in literature dealing with such small volumes [6] [7]. Composting becomes increasingly difficult to perform with the decreasing size of the system since the main parameters are no longer self-regulated. Hence, accurate monitoring can help to better understand the process and maintain its optimal operational conditions, especially in laboratory-scale systems. Composting in small controlled closed reactors can be useful, for example, to monitor gaseous production to perform a life cycle assessment of the process with a careful evaluation of fluxes and gas emissions.

In this article, we present a novel system for a scaled production of compost enhanced by an ad-hoc design of electronics capable of guaranteeing constant temperature and moisture monitoring. Furthermore, microwave imaging techniques have been applied to obtain perfect temperature control and to determine the exact degree of maturity reached by the process. Fig. 2 shows the working principle of the proposed prototype. A composter made using a salad spinner represents the heart of the entire system, the biomass placed internally, destined to become high-yield compost, is constantly monitored via a network of sensors and an array of antennas.

Two temperature and humidity sensors are connected to an electronic board that communicates, via the LoRa protocol, the acquired data to a cloud accessible via a web interface. This board has been designed to show extremely low power consumption to be left running for several months without human intervention. At the same time, the prototype includes an array of antennas that irradiates the entire composter with microwaves which, received and interpreted through the formulation of specific imaging algorithms, allow the reconstruction of the three-dimensional heat map of the entire composter. Furthermore, the intrinsic properties of the microwaves also allow the temperature of the compost biomass to rise constantly and to be controlled uniformly, accelerating the process and guaranteeing optimal parameters.

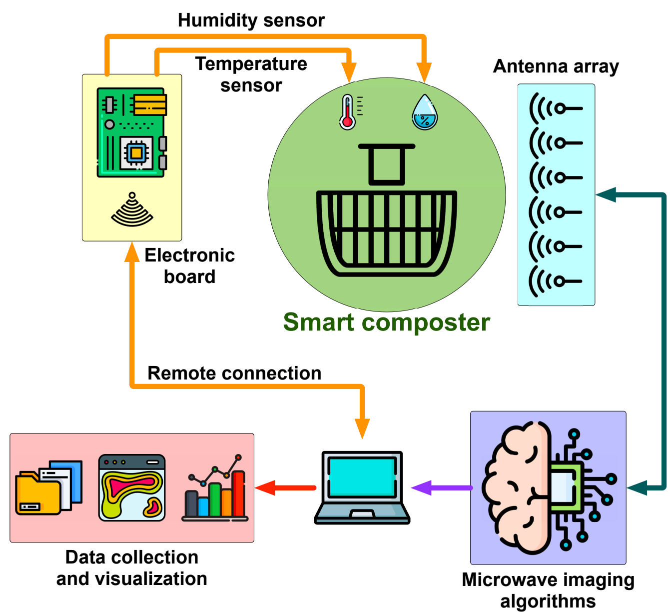

Fig. 2. Smart composter prototype working principle

The document is thus organized into three main sections, Sec. II presents the smart compost system, Sec. III presents the electronic card designed for the continuous and remote monitoring of the critical parameters and Sec. IV introduces the new approach, based on imaging techniques, for controlling and monitoring the temperature of the entire mass of compost.

II. The Compost System

The composting process works well with massive volumes, ensuring the process’s thermic auto-sustainment. Therefore, laboratory research must also expect large volumes (at least 50 liters) to ensure good results. However, lack of space and/or material limitations sometimes hinder the experimentation. We aim to evaluate the process scaling-down feasibility. Composting will be performed with a smaller quantity than usual, and sensors will be used to monitor the process and regulate the main parameters of interest to understand the most determining parameters and how they can be made scale independent.

Some experiments have been conducted using a 10-liter salad spinner. A salad spinner has been chosen because the internal colander enables the separation of the leachate from the treated solid matrix and the cover lets us have a closed system, which helps to monitor gas production. The salad spinner has been adapted to our needs and drilled on the cover to allow gas sampling and temperature measurement and on the lower side for air feeding and leachate drainage. The scheme of the system is reported in the following Fig. 3. Initially, the Organic Fraction of Municipal Solid Waste (OFMSW) was used as feedstock material, mixed with animal manure in an 80:20 ratio. Air was provided intermittently through compressed air without rigorous planning. However, the initial humidity of the feedstock material was too high, and the process did not proceed as it should. If the humidity is above the optimum range, oxygen availability is reduced, favoring the triggering of anaerobic degradation and the production of odorous gases. On the other hand, if the air is provided continuously, it dries the matrix too much, and again composting does not advance because low humidity content limits the biological activity [3]. Moreover, the probe used for temperature monitoring is placed in the middle of the matrix, where the temperature is supposed to be the highest, to avoid a too-high temperature. In this way, the temperature at the edges is not monitored and may not increase enough for the process needs. Thus, more rigorous control of these parameters should be performed to ensure that the process proceeds correctly.

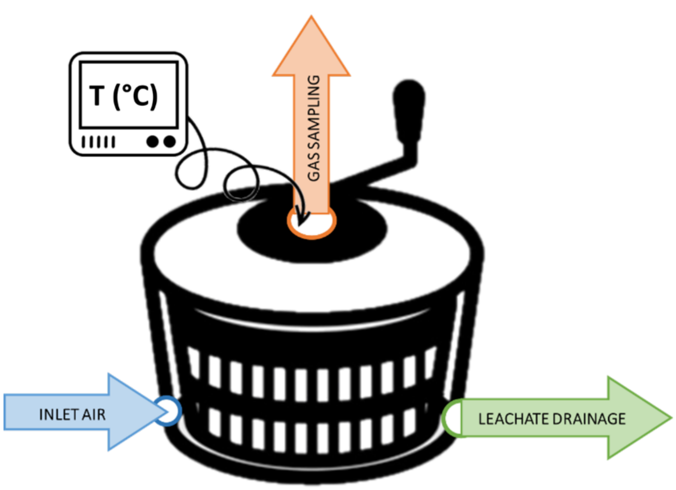

Fig. 3. scheme of the composting system in salad spinner

III. Hardware and sensors

The salad spinner alone requires manual intervention when the humidity or temperature is out of the optimal range, for example, when air needs to be inflated. Moreover, the scaled composting system requires continuous temperature and humidity monitoring for a successful outcome of the composting process. For this reason, an electronic remote control system has been developed. This card integrates the LoRa communication protocol, wich sends measurements periodically to a remote gateway enabling data collection and visualization. This long-range modulation technique operates on the license-free sub-gigahertz bands and in Italy, the frequency band adopted is 868 MHz. We adopted TTN (The Things Network) as a LoRa provider and therefore, the IoT node is registered on the TTN dashboard. This first prototype is based on the STM32WL55JC1 development board from ST Microelectronics as it already includes the LoRa radio module.

Temperature and humidity are the most important parameters to be controlled during the composting phase. Considering the harsh environment where measurements must be performed, we enriched the electronic board with waterproof sensors for temperature (DS18B20) and humidity (SEN0227) sensing. The former offers a configurable 9 to 12-bit resolution over a serial bus. The latter is based on the SHT20 temperature and humidity sensor by Sensirion, offers an I2C interface and it has encapsulation protection. The probe enclosure is made of Polyethylene waterproof materials that allow water molecules to seep in, blocking water droplets from seeping in. Data collection is performed periodically and sent to the LoRa gateway.

Air inflation can be controlled by firmware or demanded by a remote cloud system that can send inflation commands to the board. In particular, we operated the IoT node as a class A device, meaning the end node always initiates every communication. Once the uplink transmission is completed, the device opens two short receive (downlink) windows that can be used to actuate an electronic valve to inflate air in the salad spinner.

IV. Temperature Monitoring via Microwave Imaging System

Well-defined temperature profiles and homogeneous temperature and moisture distribution drive efficient composting that produces a quality fertilizer. However, due to the nature of the product and process, localized changes in temperature spike, generating spots and heterogeneous domains that degrade the overall process. Therefore, to deal with this issue and study its effects on the process, we plan to equip the proposed down-scale compost system with two temperature control alternatives. The first one employs an array of temperature sensors, as explained in the previous section, which obtains punctual temperature measures on strategic points, albeit of being invasive and have risks of damage due to environmental operating conditions in the long term. The second consists of a microwave imaging (MWI) system, which indirectly monitors the temperature distributions through the changes in the dielectric properties of the mixture undergoing a composting process, having the great advantage of working in contactless configurations and providing a global characterization of the mixture and not local information only, guaranteeing efficient composting and estimating its degree of maturity. Here is worth noticing that both approaches can work complementary and support each other. For example, the MWI system can use the sensors' measurements as reference calibration points.

MWI imaging technology exploits electromagnetic radiation of frequencies, penetrating even in opaque media, e.g., foliage, soil, wood, or compost. An MWI system illuminates the body under test with low-power electromagnetic (EM) waves that, once back-scattered, footprint the dielectric characteristics of the domain of interest and are employed to retrieve contrast variation of the complex permittivity of the inspected area (3-D images/maps). So that this technology allows determining possible inhomogeneities related to changes in water content, temperature, or other physical status affecting the electromagnetic (EM) parameters in a non-destructive, non-invasive, non-ionizing way; besides, it has low energy consumption and fast response. Due to the operation frequency band, it exploits modern high-performance microwave hardware and computing power, making the technology affordable and portable.

In the specific case of composting, there is evidence that conductivity and water content change during the composting process; thus, it is reasonable to assume that the dielectric properties of the mixture change throughout the process [8]. Furthermore, the dielectric properties of organic agricultural products are related to their fermentation and temperature, as reported in [9] for the monitoring of stored grains. Therein, the focus is to look for local increases in temperature and moisture, hot spots caused by grain fermentation, inside the grain silos. Similarly, [10] shows an increase in both permittivity and conductivity of poultry manure as the temperature goes up. Regarding to the exploiting of MWI technologies for a similar context, we can find, for example, [9], [11], where the technique is applied to the monitoring of stored grain. In [12], [13], the same technology is exploited to measure the soil moisture content. Monitoring temperature gradients by MWI has been proposed and evaluated in the biomedical field, demonstrating that an MWI system can effectively track dielectric changes associated with temperature changes [14]–[18].

When it comes to MWI device, it typically consists of an array of antennas that are responsible for probing the Domain of Interest (DoI) and gathering data on the back-scattered waves, a transceiver system that generates and collects the transmitted (Tx) and received (Rx) signals, respectively, and a processing unit running the imaging algorithm, as shown in Fig. 4.

The imaging retrieving of complex permittivity maps or variables linked to this from the EM field measurements is known as the inverse EM problem, which is non-linear and ill-posed; hence, its solution demands non-trivial processing strategies to obtain reliable results [19]. Thus, for the considered application, we look for small (regarding the probing wavelength) and low contrast variations of the observed area. This circumstance allows us to simplify the inverse problem as a linear one. Moreover, regularization is projected through an algorithm based on a truncated singular value decomposition (TSVD) and adding prior information related to the problem's physics via realistic full-wave simulations [20], [21], as illustrated in Fig. 5

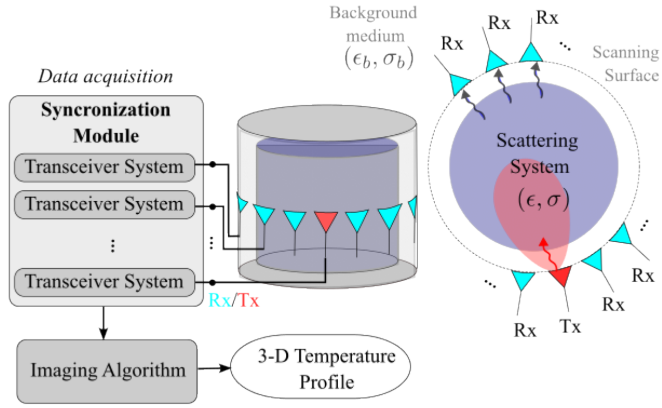

Fig. 4. Scheme of the MWI system

The inputs of the imaging algorithm are two. First, the S-parameters of an array around the DoI, which sample and describe the scenario in terms of the incoming and outgoing port waves, denoted as a_p and b_q and given at the p-th and q-th antenna ports, respectively, and second, the varying electric field distributions at t_0 and t_1, which is replaced by nominal reference one assuming a distorted Born Approximation and linearizing the problem. Therefore, the forward formulation is written as:

$$\Delta S_{p,q} = -\frac{j\,\omega\,\varepsilon_b}{2\,a_p\,a_q}\int_{\mathrm{DOI}} \mathbf{E}_p^{ref}(\mathbf{r})\cdot\mathbf{E}_q^{ref}(\mathbf{r})\,\Delta\chi(\mathbf{r},t_0,t_1)\,d\mathbf{r}, \tag{1}$$

where ΔS is the differential scattering parameter, DoI indicates the volume of the imaging domain, j is the imaginary unit, $\omega = 2\pi f$ is the angular frequency, ε is a complex

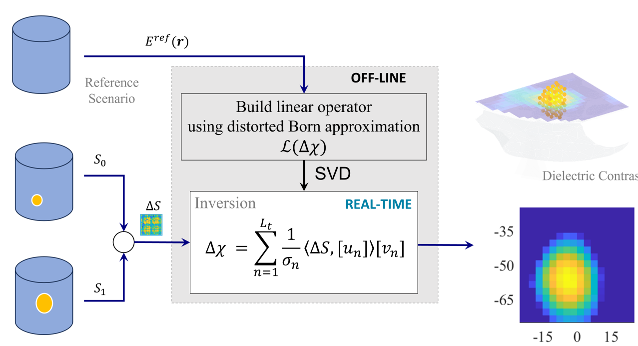

Fig. 5. Differential imaging algorithm scheme

permittivity distribution, b refers to the background, and the symbol "$\cdot$" denotes the dot product, and $\Delta\chi$ is a normalized contrast variation expressed as below.

$$\Delta\chi(\mathbf{r}; t_0, t_1) = \frac{\varepsilon(\mathbf{r}, t_1) - \varepsilon(\mathbf{r}, t_0)}{\varepsilon_b(\mathbf{r})}, \quad (2)$$

To invert Eq. 1, first, the imaging kernel is built by applying a singular value decomposition (SVD) to the discretized integral operator and decomposing it in $\langle [u], [\sigma], [v] \rangle$, where σ_n, u_n and v_n are the n-th singular value, right and left singular vectors, respectively. This part is the computationally heaviest part of the algorithm. However, it is done off-line and just once. Then, the differential contrast distribution is retrieved, projecting the scattering parameters into the decomposed kernel, a very fast stage, as:

$$\Delta\chi = \sum_{n=1}^{T} \frac{1}{\sigma_n} \langle \Delta S_{p,q}, u_n \rangle \, v_n, \quad (3)$$

where truncation index T acts as a regularizer parameter [19]. Finally, to obtain the temperature profiles, the dielectric distribution is re-mapped to the temperature one using a pre-characterization of the materials.

V. Conclusion and Perspectives

This work represents the first prototyping phase of a down-scaled homemade composter, which integrates functions of traditional multi-sensor electronic boards and microwave imaging technology. This device then guarantees full-volume monitoring of the key parameters of the composting process, compared to traditional measurement techniques. As a result, the system is expected to allow uniform heating of the biomasses, ensuring an additional level of control over the entire process.

In the near future, we expect to face an extensive measurement campaign to compare the measurements obtained with the electronic board and those obtained through imaging-based approach; subsequently, the project will integrate additional sensors and control strategies.

References

[1] Y. Nikoloudakis, S. Panagiotakis, T. Manios, E. Markakis, and E. Pallis, "Composting as a service: A real-world iot implementation," *Future Internet*, vol. 10, no. 11, 2018. [Online]. Available: https://www.mdpi.com/1999-5903/10/11/107

[2] R. Harrison, "Composting and formation of humic substances," in *Encyclopedia of Ecology*, S. E. Jørgensen and B. D. Fath, Eds. Oxford: Academic Press, 2008, pp. 713–719. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780080454054002627

[3] U. Krogmann, I. Körner, and L. F. Diaz, *Composting: Technology*. John Wiley & Sons, Ltd, 2010, ch. 9.2, pp. 533–568. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470666883.ch35

[4]

[5] B. Bian, X. Hu, S. Zhang, C. Lv, Z. Yang, W. Yang, and L. Zhang, "Pilot-scale composting of typical multiple agricultural wastes: Parameter optimization and mechanisms," *Bioresource Technology*, vol. 287, p. 121482, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960852419307126

[6] J. C. Lai, S. S. Hwang, Y. L. Then, and C. S. Lee, "Optimal aeration management strategy for a small-scale food waste composting," *Carbon Resources Conversion*, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2588913323000522

[7] J. Rose, J. C. Lai, Y. L. Then, and C. K. Vithanawasam, "Effect of external heat source on temperature and moisture variation for composting of food waste," *IOP Conference Series: Materials Science and Engineering*, vol. 1195, no. 1, p. 012058, oct 2021. [Online]. Available: https://dx.doi.org/10.1088/1757-899X/1195/1/012058

[8] A. W. Karanja, E. M. Njeru, and J. M. Maingi, "Assessment of physicochemical changes during composting rice straw with chicken and donkey manure," *International Journal of Recycling of Organic Waste in Agriculture*, vol. 8, no. 1, pp. 65–72, Dec 2019. [Online]. Available: https://doi.org/10.1007/s40093-019-0270-x

[9] J. LoVetri, M. Asefi, C. Gilmore, and I. Jeffrey, "Innovations in electromagnetic imaging technology: The stored-grain-monitoring case," *IEEE Antennas and Propagation Magazine*, vol. 62, no. 5, pp. 33–42, 2020.

[10] P. Pankaj, P. Kaur, and K. Singh Mann, "Frequency, temperature and moisture dependent dielectric properties of chicken manure relevant to radio frequency/microwave drying," *Poultry Science Journal*, vol. 9, no. 2, pp. 187–195, 2021.

[11] M. Asefi, C. Gilmore, I. Jeffrey, J. LoVetri, and J. Paliwal, "Detection and continuous monitoring of localised high-moisture regions in a full-scale grain storage bin using electromagnetic imaging," *Biosystems Engineering*, vol. 163, pp. 37–49, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1537511017303641

[12] E. Babaeian, M. Sadeghi, S. B. Jones, C. Montzka, H. Vereecken, and M. Tuller, "Ground, proximal, and satellite remote sensing of soil moisture," *Reviews of Geophysics*, vol. 57, no. 2, pp. 530–616, 2019. [Online]. Available: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018RG000618

[13] R. Lencrerot, A. Litman, H. Tortel, and J.-M. Geffrin, "A microwave imaging circular setup for soil moisture information," in *2007 IEEE International Geoscience and Remote Sensing Symposium*, 2007, pp. 4394–4397.

[14] M. Haynes, J. Stang, and M. Moghaddam, "Real-time microwave imaging of differential temperature for thermal therapy monitoring," *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 6, pp. 1787–1797, 2014.

[15] G. Chen, J. Stang, M. Haynes, E. Leuthardt, and M. Moghaddam, "Real-time three-dimensional microwave monitoring of interstitial thermal therapy," *IEEE Transactions on Biomedical Engineering*, vol. 65, no. 3, pp. 528–538, 2018.

[16] O. Fiser, M. Helbig, S. Sachs, I. L. Merunka, and J. Vrba, "Microwave non-invasive temperature monitoring using uwb radar for cancer treatment by hyperthermia," *Progress In Electromagnetics Research*, vol. 162, pp. 1–14, 2018.

[17] R. Scapaticci, V. Lopresto, R. Pinto, M. Cavagnaro, and L. Crocco, "Monitoring thermal ablation via microwave tomography: An ex vivo experimental assessment," *Diagnostics*, vol. 8, no. 4, 2018. [Online]. Available: https://www.mdpi.com/2075-4418/8/4/81

[18] H. Mozerova, R. Scapaticci, J. Vrba, and L. Crocco, "Monitoring regional hyperthermia via microwave imaging: a feasibility study," in *2020 IEEE MTT-S International Microwave Biomedical Conference (IMBioC)*, 2020, pp. 1–3.

[19] M. Bertero and P. Boccacci, *Introduction to Inverse Problems in Imaging*. CRC Press, Taylor & Francis Group, 1998.

[20] D. O. Rodriguez-Duarte, C. Origlia, J. A. T. Vasquez, R. Scapaticci, L. Crocco, and F. Vipiana, "Experimental assessment of real-time brain stroke monitoring via a microwave imaging scanner," *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 824–835, 2022.

[21] M. Ricci, J. A. T. Vasquez, R. Scapaticci, L. Crocco, and F. Vipiana, "Multi-antenna system for in-line food imaging at microwave frequencies," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 8, pp. 7094–7105, 2022.