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Eco-Friendly, High-Performance Humidity Sensor Using Purple Sweet-Potato Peel for Multipurpose Applications

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Abstract: Biomaterials offer great potential for enhancing the performance of humidity sensors, which play a critical role in controlling moisture levels across different applications. By utilizing environmentally friendly, sustainable, and cost-effective biomaterials, we can improve the manufacturing process of these sensors while reducing our environmental impact. In this study, we present a high-performance humidity sensor that utilizes purple sweet potato peel (PSPP) as both the substrate and sensing layer. The PSPP is chosen for its polar hydrophilic functional groups, as well as its environmentally friendly nature, sustainability, and cost-effectiveness. Remarkably, this humidity sensor does not require an external substrate. It exhibits a wide detection range of 0 to 85% relative humidity at various operating frequencies (100 Hz, 1 kHz, and 10 kHz) in ambient temperature, demonstrating its effectiveness in responding to different humidity levels. The sensor achieves a high sensitivity value of 183.23 pF/%RH and minimal hysteresis of only 5% at 10 kHz under ambient conditions. It also boasts rapid response and recovery times of 1 and 2 s, respectively, making it suitable for use in high-end electronic devices. Moreover, the sensor's applications extend beyond environmental monitoring. It has proven effective in monitoring mouth and nasal breathing, indicating its potential for respiratory monitoring and noncontact proximity response. These findings suggest that sweet potato peel material holds great promise as a highly stable, non-toxic, biodegradable, cost-effective, and environmentally friendly option for various domains, including healthcare monitoring.

Keywords: biomaterials; humidity sensor; purple sweet potato peel (PSPP); high sensitivity; fast response/recovery; environmentally friendly; cost-effective

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1. Introduction

Humidity sensors play a crucial role in everyday life, precisely monitoring and regulating moisture levels that affect numerous physical and biochemical processes [1–5]. Humidity sensors are used in many areas, like monitoring the environment [6], managing industrial processes [7], and assisting in healthcare [8]. These sensors make processes more efficient and improve our everyday life. Developing durable, highly responsive, and affordable humidity sensors remains a challenging task [9,10]. Even though materials like ceramics [11], semiconductors [12], and polymers [13] are typically used in sensor fabrication, the potential of biomaterials is largely untapped. With their inherent capability to absorb moisture and their environmentally friendly characteristics [14,15], biomaterials could pave the way for a new generation of humidity sensors. Biomaterials offer a multitude of benefits, such as cost-effectiveness, simplified manufacturing processes, and ease of use. Their integration aligns with the circular economy model, which emphasizes environmental sustainability—a crucial focus in our present-day world. By incorporating biomaterials into humidity sensor production, we can take significant strides towards achieving sustainable sensor fabrication and reducing our environmental footprint [16]. Selecting appropriate biomaterials for humidity sensors can be a challenging task [17], primarily due to the inherent biodegradability of these materials and the requirement for durability and stability across diverse environmental conditions. Moreover, the sensitivity of biomaterials, which directly influences their performance as humidity sensors, is a critical factor to consider [18]. The best biomaterial-based humidity sensors will be a balance of these factors, which may need new ways of processing. Some biomaterials like Aloe vera gel [19], silk [20], potato peels [21], garlic [22], leaves [23], and wood [24] have already shown potential in electronic devices due to their excellent biocompatibility and sensitivity to humidity. In recent times, scientists have been delving into the inherent physical properties of materials to bridge the gap between the remarkable advancements made in humidity-sensitive substances and their compatibility with biological systems [18]. Several studies have investigated biocompatible material-based humidity sensors. For instance, Wen et al. [25] fabricated a silk fibroin humidity sensor with sensitivity in diverse humidity environments and good repeatability and stability over time. Mandal et al. [26] used a gelatin-based humidity sensor, created using 3D printing technology, which exhibited high sensitivity and rapid response time. Guan et al. [27] also demonstrated a cellulose-based humidity sensor with flexibility and fast response time, making it suitable for wearable electronics and other applications. However, despite the progress in biomaterial-based humidity sensors demonstrated by these studies, there are several challenges that need to be addressed. These challenges include achieving high sensitivity and a wide detection range, ensuring stability and durability of biomaterials, tackling selectivity and interference issues, developing scalable fabrication techniques, and addressing cost and commercialization concerns. Overcoming these obstacles is crucial to unlocking the full potential of biomaterial-based humidity sensors across various applications, while promoting sustainability and reducing environmental impact. Researchers strive to improve the performance of humidity-sensitive materials [28] through simple fabrication methods that eliminate the need for external substrates. They aim to address challenges related to fast response and recovery times, versatile applications, and biocompatibility. Natural resources, with their broad range of potential uses, hold promise as economical and environmentally sustainable solutions. One such resource is sweet potato peel, which possesses unique qualities that make it suitable for electronic devices without extensive preprocessing. With its abundant organic content, sweet potato peel can be directly incorporated into portable electronics, minimizing the need for complex processing. Sweet potatoes are widely cultivated [29]. In the year 2020 reports, several countries emerged as key players in global sweet potato production, with China, United Tanzania, Angola, the United States of America (USA), Indonesia, and Vietnam leading the way [30]. Remarkably, China emerged as the leading global producer of sweet potatoes, boasting an impressive annual output of 49 million tons, which accounted for a significant 55% share of the total global production [31]. Sweet potatoes hold significant importance as a versatile and nutritious crop, providing essential nutrients and contributing to global food security. They are rich in complex carbohydrates, dietary fiber, vitamins (e.g., A, C, B6), and minerals (e.g., potassium, manganese). Additionally, they contain bioactive compounds, such as carotenoids and anthocyanins, known for their antioxidant properties, which contribute to potential health benefits. Sweet potatoes are not only valuable for human nutrition but also serve as a potential source of bioenergy, animal feed, and industrial applications due to their starch content and other valuable components. Moreover, their ability to thrive in diverse agro-ecological conditions, including marginal lands with minimal inputs, makes them a resilient crop choice in various regions.

In this study, we used PSPP as both a flexible substrate and a sensing element, forming a thin layer within the sensor's design. The fabrication involved creating interdigitated electrodes on the flexible peel substrate using an Ag ink pen and taking advantage of their excellent conductivity properties. The resulting humidity sensor exhibits an impressive detection range, covering a broad spectrum of humidity levels. Notably, the sensor demonstrated a high sensitivity, enabling it to detect even subtle changes in humidity levels.

Furthermore, the fast response and recovery times of the sensor were recorded. During the 25-day testing period, the sensor exhibited stable performance, further enhancing its practicality and reliability for long-term applications. Its remarkable stability allows for continuous and consistent humidity monitoring, making it suitable for various applications. The practical applications of this sensor extend beyond traditional uses, including monitoring human respiration and other noncontact (speaking and proximity) tests. Its exceptional performance as a biodegradable moisture-sensing component holds great promise for a wide range of fields and industries. In this manuscript, a new humidity sensor is introduced that uses sweet potato peel as a material. This eco-friendly and cost-effective option is easily accessible, and the sensor is simple to make, allowing for large-scale production and reproducibility. This sensor has many potential uses, including in healthcare monitoring applications, making it a groundbreaking advancement in humidity sensing.

2. Experimental Methods

2.1. Materials

We purchased organic sweet potatoes from the open market of Jeju Island, Republic of Korea, which were thoroughly cleaned with deionized water (DI) obtained from Sigma-Aldrich (Seoul, Republic of Korea). A highly conductive silver (Ag) ink pen from Circuit Scribe, Austin, TX, USA, was utilized to design Interdigital Transducers (IDTs) to assemble electrodes. Additionally, paper tape was purchased from local suppliers to increase the physical resilience of the SPP.

2.2. Sensor Fabrication

To fabricate the humidity sensor, we initiated the process by meticulously cleaning the surface of the purple sweet potato peel to eliminate any dust or contaminants. Next, the sweet potato was boiled for approximately 20 min at a temperature of 70 °C. This boiling step aided in removing the peel while potentially eliminating any remaining contaminants. After boiling, the peel was carefully removed by hand, ensuring its structural integrity throughout the process. To achieve the desired sensor substrate size of 4.5×2.5 cm^2, a precise cutting method was employed. This meticulous cutting ensured that the peel was tailored to the appropriate dimensions for our intended humidity sensor. Subsequently, the prepared peel was left to air dry for approximately 25 h. This drying period effectively eliminates excess moisture, optimizing the peel's function as both an active material and substrate for the sensor. To reinforce the strength and structure of the sensor, the dried peel was affixed onto a tape substrate. This step required careful placement and adherence of the peel onto the substrate to ensure a secure bond. Lastly, the conductive silver (Ag) interdigitated electrodes (IDTs) were meticulously assembled onto the sensor by hand. The accurate placement of these IDTs was crucial for precise humidity readings and enhanced the overall effectiveness of the sensor. Figure 1 shows the schematic diagram for the fabrication of proposed humidity sensing device. The process for creating a humidity sensor using sweet potato peel with the film structure is depicted in Figure 1.

The reproducibility of natural materials-based sensors is a challenging task that can be dealt with by considering the different parameters, as discussed here. A standardized sample preparation protocol can be developed to obtain sweet potato peels with consistent thickness. A mandolin slicer or a similar device can be used to achieve uniform thickness across multiple samples. Selecting sweet potatoes of a similar size and shape should also be considered for more consistent peels. Implementing a method to measure the thickness of each sweet potato peel before using it in the sensor fabrication process is another consideration. One should discard or categorize peels that deviate beyond an acceptable tolerance level to ensure that only peels of desired thickness are used. It is recommended to perform thorough calibration of the humidity sensor using samples with known thicknesses. This calibration data can be used to compensate for variations in thickness during actual humidity measurements. A calibration curve can be created to develop algorithms that can adjust the sensor's output based on the purple sweet potato peel thickness. The design of a humidity sensor can be optimized to make it less sensitive to thickness variations. For instance, the sensor's geometry or material properties can be modified to achieve more consistent results across a range of thicknesses. Data from multiple sensor samples with varying sweet potato peel thicknesses can be gathered. Statistical analysis can be used to understand how thickness affects sensor performance. This analysis can help to determine acceptable ranges of thickness that maintain satisfactory sensor performance. One should implement rigorous quality control measures during the sensor fabrication process and test each sensor thoroughly under controlled conditions to verify its performance and sensitivity. Furthermore, use statistical process control techniques to monitor and manage variations in sensor properties. One should consider exploring other materials that may exhibit more consistent properties and responses, reducing the reliance on sweet potato peel thickness. In addition, keep detailed records of the sensor fabrication process, including sweet potato peel thickness measurements and any adjustments made during calibration and testing. Having clear documentation will facilitate the replication of your work and allow others to reproduce your humidity sensor. Reproducibility and the mass production of devices by using natural materials like sweet potato peel can be a big challenge but this problem can be minimized by taking the above-mentioned steps.

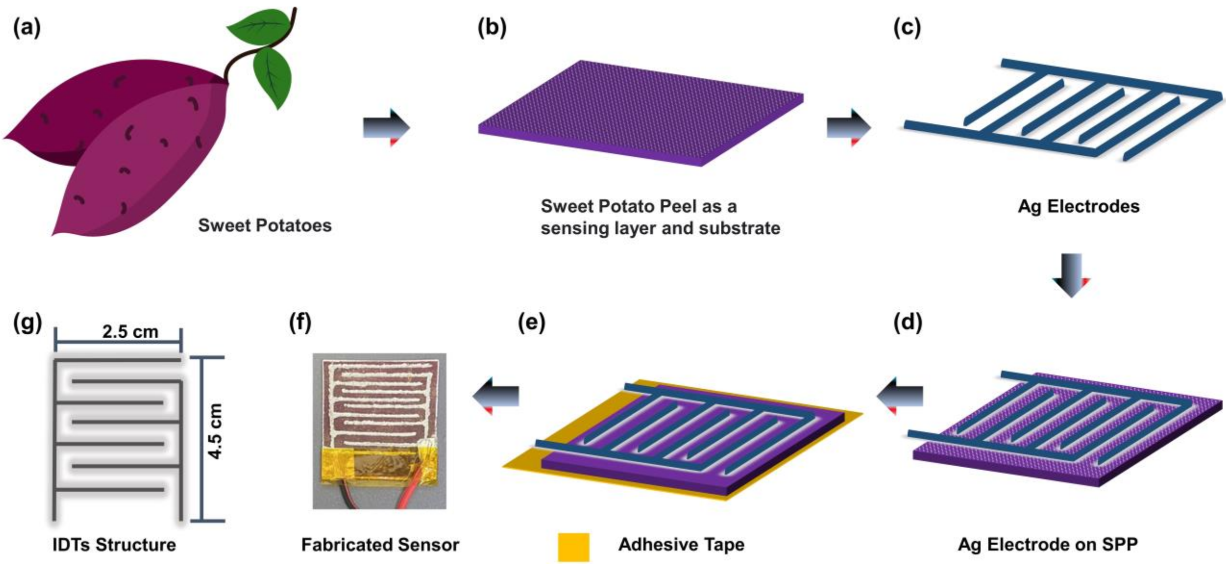

Figure 1. Process flow diagram for a sweet potato peel-based humidity sensor with the layered design of the final device. (**a**) Sweet potatoes, (**b**) sweet potato peel as a substrate, (**c**) Ag electrode, (**d**) Ag patterned by mask on purple sweet potato peel (PSPP), (**e**) PSPP attached on tape, (**f**) realized PSPP sensor, (**g**) IDTs schematic with labeled dimensions.

2.3. Characterizations

To gain a comprehensive understanding of the active substance in our sensor, we employed a range of analytical techniques. Elemental composition analysis was conducted using Energy Dispersive X-ray (EDS) spectroscopy, TESCAN, Brno, Czech Republic. The scanning electron microscope TESCAN MIRA 3 (Brno, Czech Republic) was employed to examine the sweet potato peel's surface morphology. The secondary electron detector (SE) was used for this analysis to capture the secondary electrons emitted from this peel's surface. The high voltage (HV) applied during the examination was set to 15 kV to facilitate imaging and enhance contrast. To ensure optimal imaging resolution without causing damage to the sample, which determines the electron beam size used for imaging, the working distance was set to 9.90 mm, SEM (TESCAN, Brno, Czech Republic) magnification as 654 × and view field as 424 μm allowing for a suitable balance between image sharpness and field depth while observing the sweet potato peel's surface morphology. Using the TESCAN MIRA 3 scanning electron microscope and these specific settings enabled a comprehensive analysis of the sweet potato peel's surface characteristics, providing valuable insights into its microstructure. For EDS analysis, the same equipment (scanning electron microscope TESCAN MIRA 3 (Brno, Czech Republic)) was used, which efficiently combines SEM imaging with elemental composition (EDS) analysis in a single instrument. Furthermore, a Fourier Transform Infrared Spectrometer (FT-IR) generously provided by Bruker, based in Billerica, MA, USA, enabled the identification of unique functional groups within the substance. Through these multifaceted characterization approaches, we gained a comprehensive understanding of the sensor's active material at the elemental, morphological, and functional group levels.

2.4. Sensor Evaluation

We measured the electrical capacitance using a U1733C Keysight LCR meter during our sensor assessment. The measurements were conducted at frequencies of 100 Hz, 1 kHz, and 10 kHz while maintaining a constant ambient temperature of 25 degrees Celsius. To ensure precise control over the humidity environment, we utilized a custom-built airtight plastic box equipped with a humidifier and a nitrogen (N_2) gas cylinder, as shown in Figure 2. Adjacent to the purple sweet potato peel (PSPP) humidity sensor, we placed a reference sensor (HTU-21D) and employed an Arduino circuit to accurately measure the percentage of relative humidity (%RH). To compare our custom PSPP sensor with the reference sensor, we systematically increased the humidity inside the chamber while continuously collecting data. To reset the experimental conditions, we introduced N_2 gas into the chamber through a nozzle, effectively reducing the humidity level to 0%RH. Simultaneously, we connected the LCR meter to a laptop to capture real-time capacitance spectra, ensuring precise evaluation of our sensor's performance.

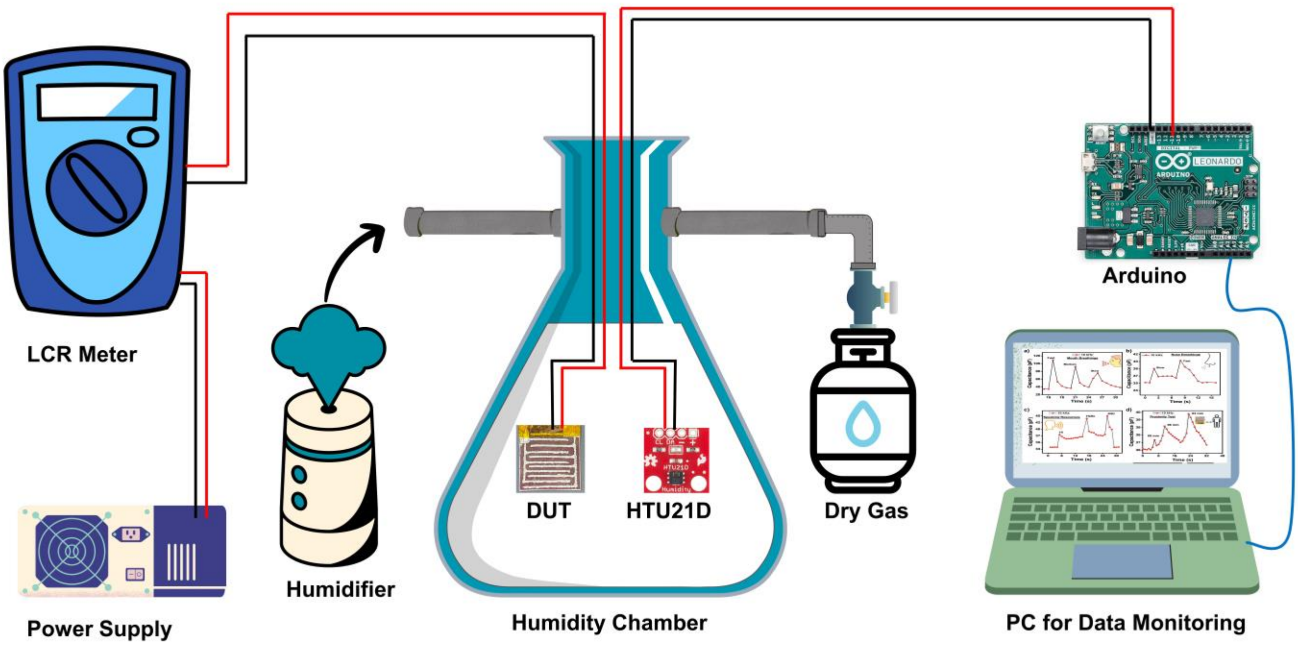

Figure 2. Experimental setup used to carry out electrical characterization of fabricated humidity sensor consisted of external power supply, LCR meter to monitor changes in capacitance, and two inlet valves to do humidify and dehumidify the chamber consisting of fabricated and reference sensor environment. The setup also included Arduino and a computer to store the obtained data.

3. Results and Discussion

3.1. Characterization of Purple Sweet Potato Peel (PSPP)

The surface morphology of the purple sweet potato peel (PSPP) was thoroughly examined using Scanning Electron Microscopy (SEM) images, as depicted in Figure 3a,b. These SEM images reveal distinct surface characteristics, such as micro-level roughness and the presence of pores. These features play a vital role in the functionality of the humidity sensor by facilitating the absorption of water molecules, thereby enhancing its humidity measurement capability.

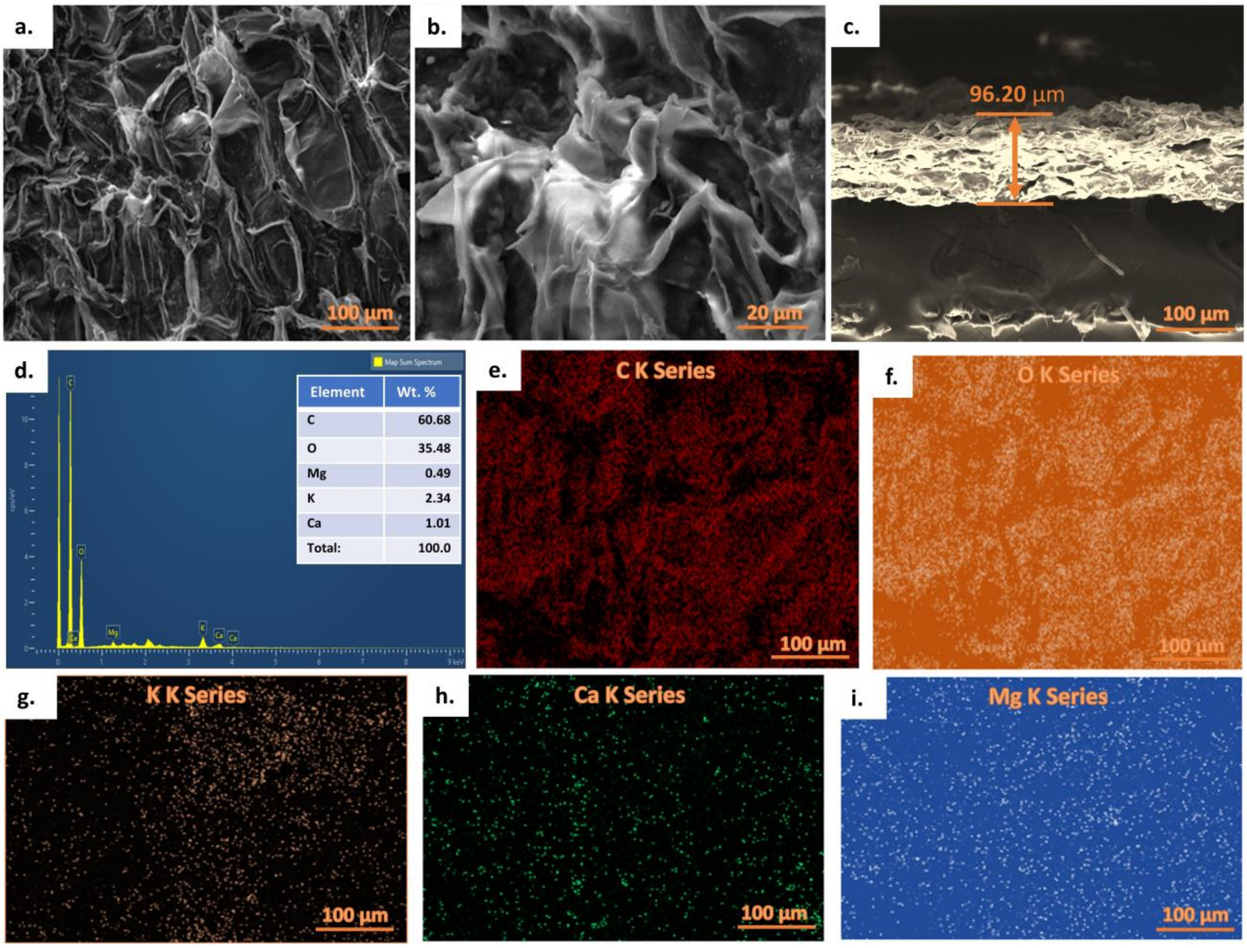

Figure 3. Surface characterization of sweet potato peel. (**a**,**b**) Field-Emission Scanning Electron Microscopy (FESEM) images at two different resolutions (100 µm and 20 µm) showcase the porosity and extensive surface area of the sweet potato peel. (**c**) Cross-section FESEM image highlights the active layer thickness, which measures 96.2 µm. (**d**) Energy-dispersive X-ray spectroscopy (EDS) reveals the concentration of various elements within the sweet potato peel. (**e**–**i**) Elemental analysis results demonstrate the presence of C, O, K, Ca, and Mg in the sensor's composition.

The PSPP exhibits a relatively uniform thickness throughout the sample, averaging at approximately 96.20 µm, as shown in Figure 3c. This uniform thickness is crucial in ensuring consistent and reliable sensor readings. Figure 3d presents the EDS spectrum, revealing the elemental composition of the sample showing the C, O, Mg, K, and Ca elements in the active layer. The primary components identified were carbon (60.68%) and oxygen (35.48%). Additionally, smaller amounts of magnesium (0.49%), potassium (k) (2.34%), and calcium (Ca) (1.01%) were also detected. These findings are supported by the respective X-ray series, including C K, O K, K K, Ca K, and Mg K, displayed in Figure 3e–i.

The presence of potassium (K), calcium (Ca), and magnesium (Mg) in the purple sweet potato peel-based humidity sensor, as identified through Energy-Dispersive X-ray Spectroscopy (EDS), may not be directly essential for humidity sensing. However, it can play a role in influencing the overall sensor performance and characteristics. Potassium, calcium, and magnesium are typically present in natural materials like sweet potato peels and contribute to the overall elemental composition of the substrate. The presence of potassium, calcium, and magnesium might affect the peel's mechanical stability and durability, enhancing its robustness as a sensing material. These elements can interact with water molecules in the peel, potentially influencing the peel's water adsorption and desorption capabilities, which are essential for accurate humidity sensing. These ions also help to increase dielectric constant that enhances sensitivity towards relative humidity changes [32,33]. While carbon and oxygen are the primary elements and likely contribute most significantly to the humidity-sensing properties, the presence of other elements can still impact the material's behavior and interactions with water molecules. However, potassium, for instance, has been studied in other humidity sensors as a dopant or additive that can enhance the sensor's humidity response and sensitivity. Research has shown that incorporating potassium into humidity-sensing materials can promote surface proton conduction and increase the sensor's response to changes in humidity levels. In summary, while potassium, calcium, and magnesium may not directly contribute to humidity sensing, they can influence the overall behavior and properties of the sweet potato peel material, which affects its suitability as a humidity sensor. The combination of different characteristics, including dielectric properties, mechanical stability, and water adsorption behavior, collectively makes sweet potato peel a viable option for humidity sensing applications. A thorough understanding of these factors is crucial to design and optimize a high-performance sweet potato peel-based humidity sensor.

The biodegradable purple sweet potato peel humidity sensor (PSPPHS) demonstrated exceptional accuracy in measuring a wide range of humidity levels (0% to 85%RH), highlighting its environmentally friendly nature. Operating at frequencies of 100 Hz, 1 kHz, and 10 kHz (Figure 4a–c), the sensor consistently provided reliable and precise measurements.

The results indicate that the purple sweet potato peel-based humidity sensor exhibits different sensitivities to humidity changes at various frequencies, as shown in Figure 4d. Below 60% relative humidity (RH), the normalized capacitance ($\Delta C/C_o$) changes at 100 Hz are relatively small, suggesting a lower sensitivity. However, above 60%RH, the sensor becomes highly sensitive, showing more pronounced changes in normalized capacitance at higher frequencies like 1 kHz and 10 kHz. This emphasizes the crucial role of operating frequency in determining the sensor's performance. Notably, the sensor works acceptably across the entire humidity range, a significant advantage as it allows for reliable and accurate humidity monitoring in diverse environmental conditions. The sensor's responsiveness has been assessed using Equation (1). The overall sensitivity response of the suggested sensor was determined using the following formula, where S_x represents the overall variance of the sensitivity response.

$$S_x = ((C_{RH} - C_{RHo})/C_{RH}) \times 100\% \quad (1)$$

The capacitances at different humidity levels, %RH and 0 %RH relative humidity, representing the sensor's sensitivity response at 10 kHz, were denoted as C_{RH} and C_{RHo}, respectively. As depicted in Figure 4e, the measured values exhibit an almost linear increase, as in the measured sensitivity of 183.23 pF/%RH, demonstrating the sensor's ability to respond to varying humidity levels. The SPPHS exhibited a rapid response time of 1 s, enabling real-time monitoring and providing immediate feedback even in dynamic environmental conditions. Moreover, the recovery time of only 2 s minimized idle time between humidity readings, allowing for continuous and uninterrupted monitoring Figure 4f. The humidity sensor exhibited excellent response during adsorption and desorption, with minimal hysteresis of only 5% at 10 kHz, as illustrated in Figure 4g. Based on sweet potato peels, the humidity sensor underwent rigorous performance evaluations over 25 days, consistently demonstrating remarkable results, as depicted in (Figure 4h).

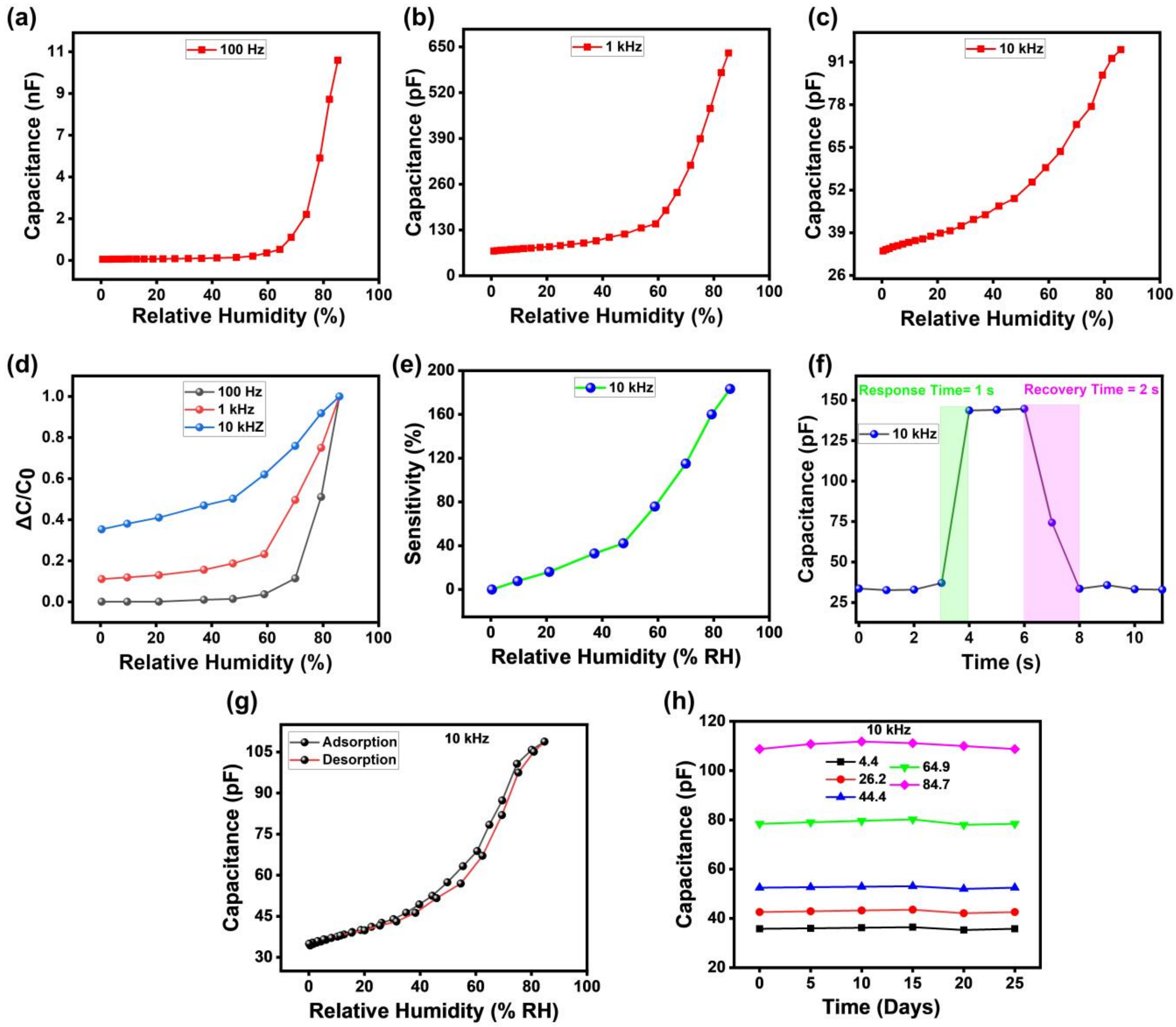

Figure 4. (**a**) Capacitance values of PSPP humidity sensor at operating frequency of 100 Hz (**b**) Capacitance values of the proposed sensor at 1 kHz. (**c**) Capacitance values of the proposed sensor at 10 kHz. (**d**) Normalized capacitance response of the proposed sensor at different frequencies for comparison purpose 100 Hz, 1 kHz, and 10 kHz. (**e**) Sensitivity response of the proposed humidity sensor. (**f**) Graph of response and recovery times of PSPP. (**g**) The reaction of the suggested sensor to adsorption and desorption. (**h**) Capacitive response curves for the stability of proposed sensor over the period of 25 days.

The proposed sweet potato peel-based humidity sensor outperforms other biomaterials-based humidity sensors on multiple fronts. Firstly, our manuscript introduces novelty to the subject area by being the first to utilize purple sweet potato peel as the sensing material, setting it apart from previously published research, as listed in Table 1. In comparison to the sensors described in the literature, our sensor exhibits the rapid response and recovery time of 1 and 2 s and enables real-time measurements, proving crucial for applications demanding swift sensing capabilities. Moreover, the sensor exhibits a high sensitivity of 183.23 pF/%RH, which allows for the precise detection of even minor fluctuations in humidity levels. The sensor's durability, sustaining optimal performance over 25 days, underscores its long-lasting functionality. This unique amalgamation of features positions our PSPP-based humidity sensor as the optimal choice, and sensitive humidity-sensing capabilities across a broad spectrum compared to other biomaterials-based humidity sensors. These advantages make our humidity sensor a promising and innovative option for humidity sensing applications. Compared with other biomaterials-based humidity sensors, the sweet potato peel-based sensor demonstrates superior performance due to its unique combination of hydroxyl groups, wettability, and hygroscopic properties. These factors make it highly responsive and sensitive to changes in humidity levels, providing accurate and reliable humidity-sensing capabilities for various applications.

Table 1. This study compares humidity sensors' features and production processes made from various natural materials.

Natural Material	Stability Range	Response/Recovery Time	Fabrication Technology	Sensitivity	Stability
Chitosan [34]	18–70%RH	_	Solution casting method	_	5 min
Potato peel [21]	10–90%RH	8/12 s	Peeling	70 kΩ/%RH	One week
Egg white [35]	10–85%RH	1.2–1.7 s	Spin coating/ thermal evaporation	50 kΩ/%RH	36 h
Silk [36]	40–99%RH	37/- s	_	0.99 nm/%RH	Two weeks
Halloysite nanotubes [37]	0–91.5%RH	0.7/57.5 s	Coated with paint brush	_	35 days
Collagen [38]	50–90%R.H	_	_	0.1287 µA/%RH	5 min
Wool [39]	16–82%RH	36/55 s	_	855.66 %	_
Biomass ash [40]	15–90 %RH	2/10 s	Screen printing/drop-casting	1×10^6	1–8 weeks
Sepiolite [41]	10.9–91.5%RH	528/26 s	Screen printing	_	10 cycles
Purple Sweet Potato Peel [This work]	0–85%RH	1/2 s	Peeling	183.23 pF/%RH	25 days

3.2. Conduction Mechanism of SPPHS

Our study harnesses the unique conduction mechanism of purple sweet potato peel (PSPP) to develop a highly effective humidity sensor. Fourier Transform Infrared (FTIR) spectroscopy was employed to identify the specific functional groups present in the peel, each playing a crucial role in humidity sensing, shown in Figure 5a. The hydroxyl groups (O-H) exhibit a sensitivity to moisture, evident in their peak between 3400 and 3650 cm^{-1}. These groups form hydrogen bonds with water molecules, altering the peel's conductivity as humidity levels change. The conductivity variations observed reflect this sensitivity. The C-H functional group contributes to the peel's structural integrity and stability, as indicated by a peak at 2921 cm^{-1} in the FTIR spectrum. The carbonyl groups of the C=O functional group, denoted by a peak at 1693 cm^{-1}, may also exhibit humidity sensitivity. The interaction of these groups with water molecules can influence the peel's conductivity and its response to humidity changes. While the C=C functional group does not directly participate in humidity sensing, it can impact the presence of aromatic combinations within the peel. Other oxygen and carbon groups, represented by a peak at 1364 cm^{-1} (C-O-C), contribute to the peel's overall stability and structure. At around 700 cm^{-1}, the peak may correspond to out of plane bending of aromatic compounds. The peak around 756 cm^{-1} could potentially correspond to a C-H out of plane bending mode in substituted benzene rings [42].

The proper functioning of the PSPP-based humidity sensor is heavily reliant on the hopping mechanism of proton conduction and the adsorption of water molecules, as shown in Figure 5b. Protons (H+) move between hydroxyl (OH^-) groups within the material, aided by the hopping mechanism, to achieve proton conduction. The sensor's surface contains hydroxyl groups that water molecules from the environment can adsorp onto as humidity levels change. This causes hydrogen bonds to form between the hydroxyl groups and water molecules. As more water molecules are adsorbed with rising humidity levels, protons can move more readily through the hopping mechanism. As a result, the electrical conductivity of the sensor increases, enabling it to recognize and respond to changes in humidity levels accurately. Therefore, the interaction between water molecules and functional groups in the sensor's material is critical for its sensitivity and response to varying humidity levels. The capacitive-type humidity sensor with a sweet potato peel as the active layer operates based on the variations in the sweet potato peel's dielectric properties in response to humidity changes. It functions by measuring the capacitance changes between two conductive plates, with the sweet potato peel acting as the dielectric material. As the humidity in the surrounding environment fluctuates, the sweet potato peel absorbs or releases water vapor, leading to changes in its moisture content and dielectric constant. This dielectric constant reflects the material's ability to store electrical energy in an electric field. The sensor's capacitance is directly related to the area of the plates and the dielectric constant of the material between them, while inversely related to the distance between the plates. Thus, the humidity-induced variation in the sweet potato peel's dielectric constant causes changes in the sensor's capacitance. The relationship between capacitance and humidity is typically nonlinear, following a specific curve or response profile, which can be determined through calibration and testing. By monitoring capacitance changes, the humidity sensor can convert these variations into an electrical signal that indicates the surrounding humidity levels. The dielectric properties of sweet potato peel, like all materials, depend on its response to an electric field. These properties change with humidity levels as the peel interacts with water vapor in the environment. The key properties for humidity sensing are the dielectric constant (ε) and the dielectric loss factor (tan δ). The dielectric Constant (ε) measures a material's ability to store electrical energy under an electric field. In a capacitive humidity sensor with sweet potato peel as the active layer, the dielectric constant changes with the absorbed or released water vapor. Higher humidity leads to an increase in the peel's dielectric constant, while lower humidity causes a decrease. The dielectric Loss Factor (tan δ) represents energy lost as heat during polarization under an electric field. In the humidity sensor, the dielectric loss factor changes with humidity due to peel-water–vapor interactions. As humidity changes, the water molecules' polarization in the sweet potato peel alters, affecting both the dielectric constant and the dielectric loss factor. The specific dielectric properties of sweet potato peel and their humidity response can be influenced by factors like variety, maturity, and environmental conditions. Carbohydrates, which are rich in hydroxyl (OH) and carbonyl (C=O) groups, are primary contributors to humidity sensing in biomaterials. Sweet potato peels have a higher abundance and even distribution of these functional groups, enhancing their sensitivity to humidity changes. EDS analysis of sweet potato peel (Figure 3d) clearly shows that the concentration of carbon (C) and oxygen (O) is maximum in sweet potato peel, and both these atoms play a vital role in the formation of hydroxyl and carbonyl functional groups as these functional groups are composed of carbon and oxygen atoms. FTIR result (Figure 5a) also confirms the presence carbonyl and hydroxyl functional groups in sweet potato peel. Carbon and oxygen atoms are the building blocks for the formation of hydroxyl and carbonyl functional groups (present in abundance in sweet potato peel), which are essential components of many biomolecules and contribute to humidity sensing capabilities. Sweet potato peels possess a higher surface area [43,44] and porosity (shown in SEM image of Figure 3a,b), facilitating more interactions between water molecules and OH/C=O groups, resulting in a rapid response to humidity changes. The microstructure of sweet potato peels, such as micro-cracks and pores, enhances water absorption, thus improving the sensor's performance. While sweet potato peels also contain vitamins, proteins, dietary fiber, and fats, they do not play a major role in humidity sensing [45–48]. These constituents might influence the material's properties but are not the primary contributors to humidity sensing.

In summary, high concentration of carbonyl/hydroxyl functional groups, high porosity, and high surface area are main reasons for the excellent performance of the sweet potato peel-based humidity sensor. It is crucial to acknowledge that the field of humidity sensing using biomaterials is continuously evolving, and further research might explore the potential of other functional groups in humidity sensing.

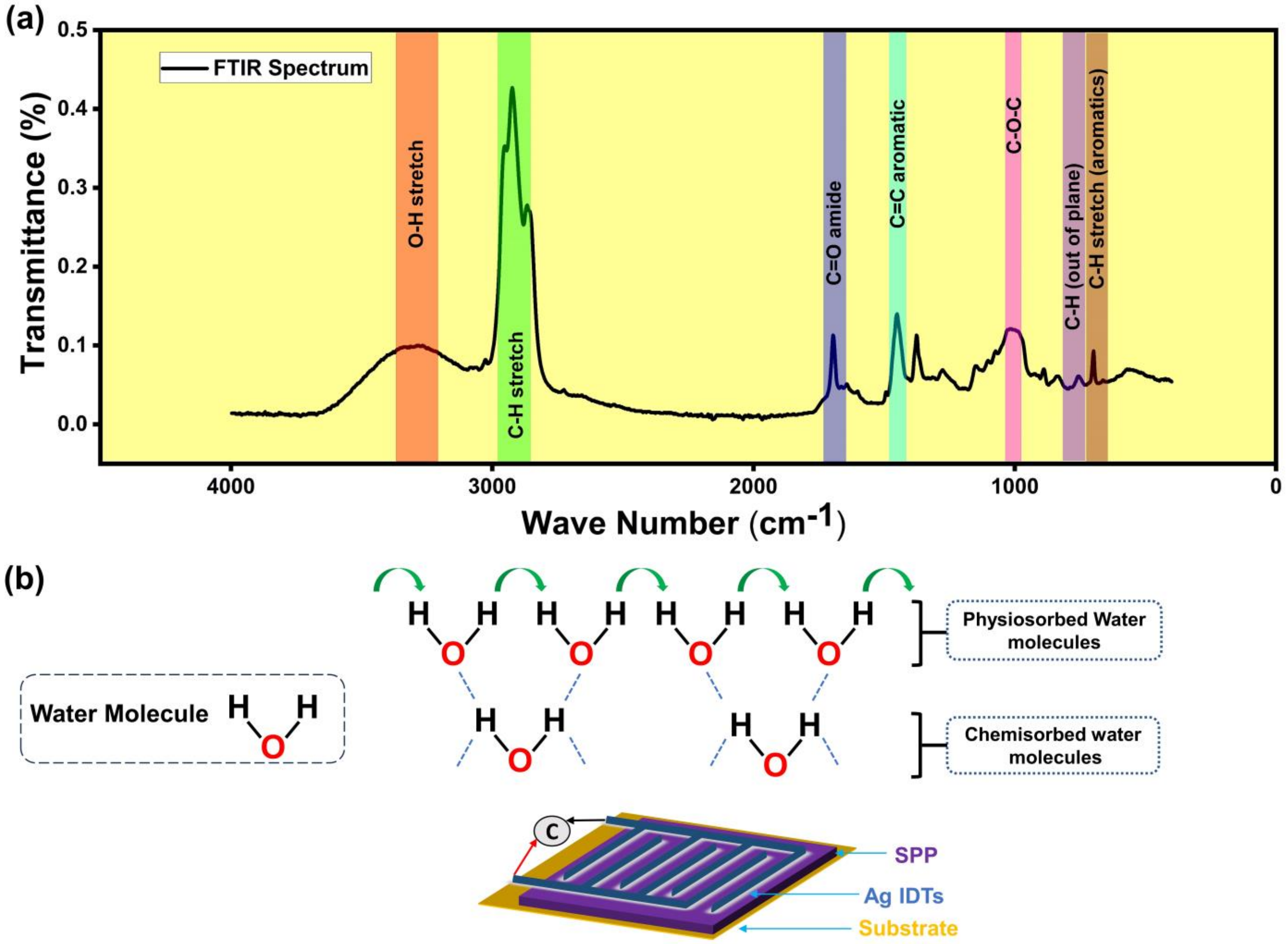

Figure 5. (**a**) The FTIR spectrum of a sweet potato peel with all the distinctive peaks, and (**b**) illustration of the hopping mechanism of proton conduction and the adsorption of water molecules in a schematic diagram.

3.3. Applications of SPPHS

Our humidity sensor demonstrates an application-specific response rate, making it highly versatile for a wide range of uses, including long-term monitoring, performance optimization, and environmental studies. Its exceptional sensing capabilities allow for various applications, such as monitoring human health by detecting water vapor in breath. The sensor exhibits rapid and precise responses to even subtle changes in humidity levels, whether from breathing through the nose or mouth, or through noncontact proximity. It is crucial to consider the impact of mouth breathing on respiration monitoring, as indicated by the significant change in capacitance from 110 pF to 38 pF. This change affects electrical capacitance during different breathing patterns, as depicted in Figure 6a,b, which illustrates nasal responses during slow and rapid breathing. Furthermore, Figure 6c demonstrates the sensor's capacitance response to spoken phrases, such as "Hi", "Hello", and "JNU", with correspond to capacitance values of 38 pF, 43 pF, and 46 pF. These sensors can be integrated into intelligent home systems to adjust air conditioning and ventilation based on detected humidity levels from speech, leading to more accurate speech recognition and improved human–machine interaction. Capacitance values exemplify the potential impact of speech-enabled humidity sensors in various fields, providing users with enhanced experiences and facilitating effective communication. Additionally, the humidity sensor is capable of detecting moisture in noncontact environments and exhibits different capacitance responses at varying distances, as depicted in Figure 6d. This versatility enables a range of applications, including object detection, proximity sensing, and industrial process monitoring. These sensors offer flexibility in noncontact humidity detection, enabling precise monitoring and adjustments in diverse settings. It is important to note that the specific capacitance values and distances mentioned are hypothetical and may vary based on the sensor's design and calibration. Real-world implementations would involve calibrating the sensors to provide accurate and reliable humidity information during noncontact proximity testing.

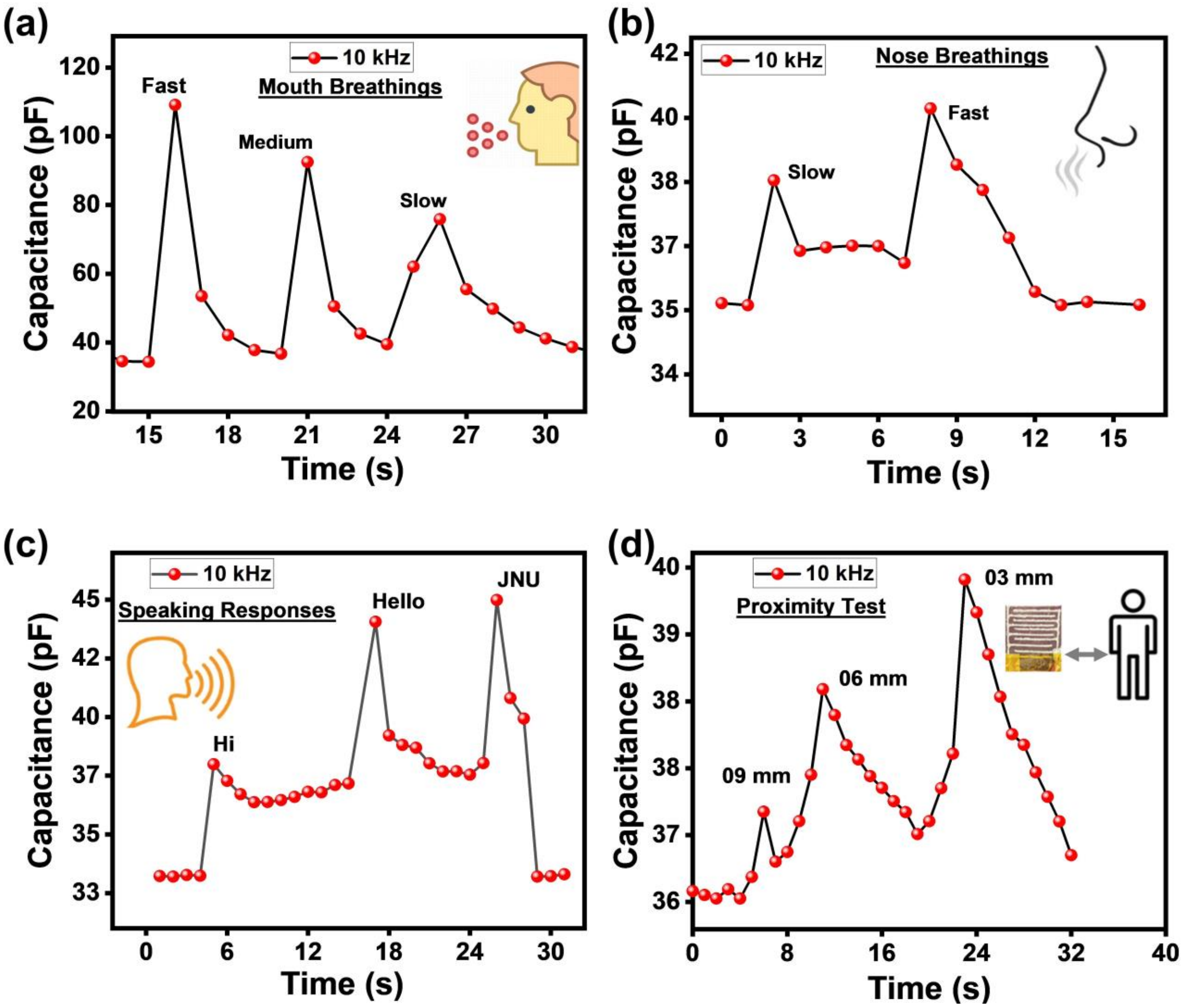

Figure 6. Capacitance response of the proposed sensor for various applications: (**a**) capacitance response through my mouth breathing, (**b**) capacitance response through my nasal breathing, (**c**) response of the speaking. (**d**) Response of the noncontact proximity test by human hand with 9 mm, 6 mm, and 3 mm.

4. Conclusions

In conclusion, this study has successfully developed an environmentally friendly humidity sensor using purple sweet potato peel, a biodegradable material. The sensor demonstrates exceptional wettability and superior sensing capabilities, positioning it as a promising tool for applications in human breath monitoring and healthcare. Through this pioneering research, we have shown that the capacitance humidity sensor effectively detects humidity levels in purple sweet potato peel within a range of 0–85%RH. Notably, the sensor exhibits remarkably fast response and recovery times of only 1 and 2 s, respectively. At a frequency of 10 kHz, it achieves a high sensitivity of 183.23 pF/%RH, surpassing other humidity sensors made from organic materials. This initiative to utilize non-toxic and biodegradable materials in environmental sensing opens doors for a wide array of applications and promotes the adoption of sustainable, cost-effective, and disposable materials in sensor development.

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