Chuang et al, Gerontechnology (2026) 25:4
https://doi.org/10.4017/gt.2026.25.4.1667.6

Development of an intelligent gas-sensing fecal collection system for bedridden and incontinent people: A sustainable approach to smart seniors care

Fu-Jung Chuang MS[a,†], Yueh-Heng Chiu BBA[a,†], Chia-Hsin Chen MD PhD[b,c,d,e]

[a]Department of Post-Baccalaureate Medicine, College of Medicine, Kaohsiung Medical University, Kaohsiung, Taiwan; [b]Department of Physical Medicine and Rehabilitation, Kaohsiung Medical University Hospital, Kaohsiung, Taiwan; [c]Department of Physical Medicine and Rehabilitation, School of Medicine, College of Medicine, Kaohsiung Medical University, Kaohsiung, Taiwan; [d]Department of Physical Medicine and Rehabilitation, school of Post-Baccalaureate Medicine, College of Medicine, Kaohsiung Medical University, Kaohsiung, Taiwan; [e]Neurotechnology and Assistive Technology Research Center, Kaohsiung Medical University, Kaohsiung, Taiwan

†Fu-Jung Chuang and Yueh-Heng Chiu contributed equally to this article.
**Corresponding author: chchen@kmu.edu.tw*

Abstract

Background: Bowel incontinence is a persistent challenge among bedridden and disabled senior patients, often leading to adverse clinical outcomes such as skin infections and significant caregiver burden. Conventional adult diapers generate substantial environmental waste, and existing diaper-based monitoring systems are often seen with delayed response times and high costs. Therefore, there is a critical need for more advanced and sustainable alternatives.
Research aim: This study aims to develop and evaluate an "Intelligent Gas-Sensing Fecal Collection System". The goal is to provide an eco-friendly solution that utilizes biodegradable materials, real-time biosensing, and Bluetooth communication to improve caregiving efficiency, user hygiene, and patient dignity.
Methods: The system integrates a reusable sensor module featuring a semiconductor for detection of fecal gases, Bluetooth Low Energy (BLE) transmission, and a biodegradable collection bag composed of pineapple leaf fibers and polylactic acid (PLA). The proposed system's performance was evaluated through laboratory gas exposure tests and a usability trial involving 30 caregivers.
Results: Laboratory tests confirmed that the sensor detected 1 ppm of ammonia within 60 seconds, triggering an immediate wireless notification. In the usability trial, the proposed system demonstrated considerable potential for caregiving efficiency improvement, achieving an 87% reduction in caregiver workload and a 75% decrease in cleaning time. Furthermore, 83% of caregivers reported enhanced patient dignity and comfort.
Conclusion: The smart fecal collection system offers an effective and sustainable solution for senior care. By reducing labor intensity, the proposed system demonstrates high clinical potential. Future work will focus on scaling production, optimizing in IT infrastructure, and integrating AI-based predictive analytics.

Keywords: smart senior care, fecal collection, biosensor, sustainability, gerontechnology

Introduction

With the global population aging at an unprecedented rate, bowel incontinence has become a significant public health and caregiving challenge, particularly for long-term care institutions. In Taiwan alone, over 760,000 individuals are affected by functional disabilities, and over 500,000 require adult diapers for daily care. Routine diaper checking and changing are the cornerstone of traditional caregiving protocols, which often result in high labor intensity, increased caregiver fatigue, and prolonged exposure to fecal matter for patients. Such prolonged exposure significantly increases the risk of infection, pressure ulcers, skin irritation, and emotional distress. Furthermore, conventional diapers made primarily from petroleum-based plastics contribute to approximately 1000 grams of CO_2-equivalent emissions per unit—normalized units of greenhouse gas emissions against carbon dioxide. With the increasing demand for adult diapers, the resulting incontinence waste creates an escalating environmental burden, which is projected to significantly outpace infant diaper waste (Brewster et al., 2022). Existing urine-detection sensors are often unable to detect fecal discharge appropriately, leading to extended response times and hygiene complications.

Early studies were reviewed for a better understanding of the environmental and logistical limitations of traditional adult diapers. According to an updated lifecycle assessment by the Department for Environment, Food and Rural Affairs (Defra, 2023), approximately 63% of the carbon footprint of disposable diapers is generated through the production of the materials, particularly from the petroleum-based polymers. Similarly, Muthu et al. (2013) estimated the emissions of adult diapers at 781–1125 grams of CO_2-equivalent per item, driven primarily by the manufacturing of superabsorbent polymers and non-recyclable plastic covers. In the same study, reusable protective pants were shown to have the lowest footprints, with carbon emissions as low as 220–275 grams per use. However, despite these environmental benefits, reusable products are not widely adopted in clinical settings, likely due to logistical challenges in cleaning and infection control requirements.

Recent advancements in semiconductor gas sensors have also enabled rapid and precise detection of volatile compounds at trace concentrations. The study by Machín et al. (2023) on nanomaterial-based sensors demonstrated stable sensitivity to ammonia concentrations approaching 1 ppm, which provided a solid technological foundation for early fecal matter detection. Furthermore, experiments carried out by Carusone et al. (2021) utilizing BLE (Bluetooth Low Energy) highlighted the potential integration of low-power wireless communication with biosensors that can be employed for the transmission of medical data. Notably, European initiatives, such as the imec.icon project Smart Diapers (2023), have demonstrated the feasibility of separating reusable electronic modules from disposable sensing layers to optimize cost-efficiency and waste reduction. Combining these technologies forms the basis of a new fecal detection system that unites sustainability and clinical feasibility.

Methods

System design and components

The Intelligent Gas-Sensing Fecal Collection System comprises three interdependent modules that collectively enable reliable detection, communication, and waste collection:

1. Collection Bag: The collection bag, shown in Figure 1, is constructed from biodegradable materials, specifically a composite of recycled pineapple leaf fibers and biodegradable polylactic acid (PLA). Pineapple leaf fibers have been identified as a superior reinforcement agent for polymer composites due to their mechanical strength and cost-effectiveness (Sethupathi et al., 2024). With this composition, each collection bag is capable of withstanding a load of up to 1 kg of stool, and the materials can fully degrade into water (H_2O) and carbon dioxide (CO_2).

2. Sensor Module: The sensor module incorporates semiconductors that act as an electronic nose and are capable of sensing gases released during defecation. While the low-cost gas sensing chip is disposable, the remainder of the sensor module is reusable. The sensor module is water-resistant and highly sensitive, showing a consistent capability to detect ammonia levels as low as 1 ppm.

3. Wireless Transmission: The wireless communication module utilizes a Bluetooth Low Energy (BLE) protocol to transmit alerts to caregivers on cell phones or a centralized nurse dashboard. Caregivers are immediately alerted to the defecation event without the need for physical examination.

The schematic diagram of the smart fecal collection system is shown in *Figure 2*.

Laboratory testing and experimental validation

To validate the proposed system's performance, multiple experiments were conducted. Gas exposure experiments were performed in controlled laboratory settings that simulated fecal gas atmospheres to assess sensor responsiveness and detection accuracy. To ensure data reproducibility, calibration procedures were performed before each experimental batch. The sensor was pre-heated in filtered ambient air and stabilized to establish a baseline using zero-gas calibration. The testing environmental conditions were maintained at a temperature of 25–28°C and a relative humidity of 40–60%. The Metal Oxide Semiconductor (MOS) sensor used in the experiments operated based on broad-spectrum response patterns; therefore, rather than targeting a single gas type, the experiments focused on the overall gas response pattern. Similar to electronic nose systems (Gardner & Bartlett, 1999), the MOS sensor demonstrated high sensitivity to ammonia while exhibiting characteristic cross-reactivity to other reducing gases (e.g., sulfides) and limited response to non-reducing gases such as CO_2. This characteristic facilitates the detection of the overall fecal odor profile.

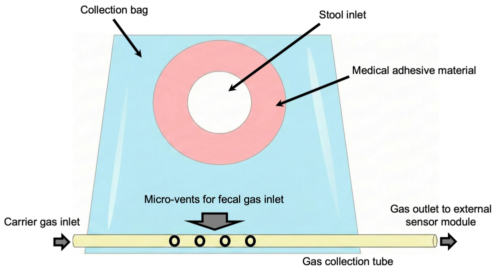

Figure 1. Prototype of the biodegradable collection bag for the smart fecal collection system. The device interface uses medical-grade adhesive material for secure attachment to the user's perianal region.

To evaluate the functional feasibility and user acceptance of the smart fecal collection system prototype, a prospective, non-controlled pilot usability study was carried out. The study was conducted with 30 caregivers, who were the primary caregivers of the selected bedridden patients in the university hospital. The study protocol involved the practical application of the collection bag to bedridden patients during their daily care routine. Usability was quantitatively evaluated by measuring time-to-completion (cleaning and replacement duration), while patient comfort and overall caregiver satisfaction were assessed through structured interviews and qualitative feedback. These metrics were selected to comprehensively validate the proposed system's technical reliability, caregiving efficiency, and its potential impact on patients' quality of life.

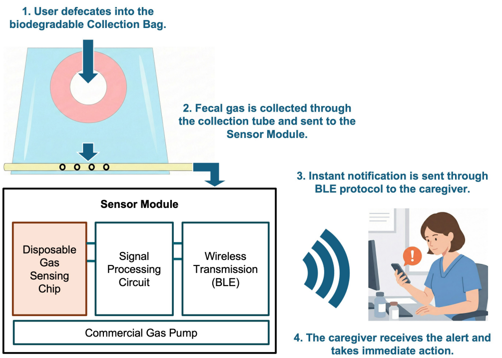

Figure 2. Schematic representation of the Intelligent Gas-Sensing Fecal Collection System. The diagram illustrates the workflow where fecal gases are transported via the collection tube to the sensor module, triggering real-time wireless notifications to caregivers.

Results

Detection performance

The results of the gas exposure experiments confirmed that the sensor maintained high sensitivity and response speed consistently. In controlled laboratory conditions, the sensor responded to 1 ppm ammonia within 60 seconds, with clear and reproducible output signals. The BLE transmission module demonstrated stable and instant data communication, ensuring that caregivers received alerts in real-time. This instantaneous feedback minimized fecal exposure time, thereby lowering the risk of skin irritation and infection in bedridden patients.

User evaluation

The pilot usability study conducted with 30 caregivers revealed highly positive outcomes. Approximately 87% of the caregivers reported a significant reduction in daily inspection workload, and the cleaning time was reduced by 75%, from eight minutes for regular diapers to approximately two minutes with the application of the proposed system. Less than 10% of the patients experienced mild skin reactions, such as transient rashes, during the course of the study, indicating good dermatological compatibility. Moreover, 83% of the caregivers noted considerable improvement in patient comfort and dignity. Overall caregiver satisfaction reached 90%, indicating favorable feedback on responsive alerting, the minimized need for routine diaper checks, and the ease of use of the proposed system.

Discussions

The results demonstrate that integrating biosensing and wireless transmission technologies into senior care products can substantially enhance caregiving efficiency while advancing sustainability goals. Real-time gas detection effectively bridges the gap between patient needs and caregiver response, improving hygiene management and overall quality of life. In comparison with traditional diaper-based care, the smart fecal collection system reduces caregiver workload by eliminating unnecessary diaper checks and ensuring that excretion is managed promptly and discreetly.

Environmentally, the application of biodegradable composites contributes significantly to the circular economy and materials engineering for sustainability. The integration of biodegradable polymers, such as PLA, in biosensors has become increasingly prominent, as seen in recent platforms for urine analysis, including those by Gomes et al. (2023). This supports our choice of a combination of PLA and pineapple leaf fibers for the collection bag composite. Pineapple leaf fibers, which are otherwise discarded as plantation by-products, are a key component of the Green Cycle Materials™ (GCM) used in this study. This material is free from petroleum-derived plastics, i.e., PP (Polypropylene), PS (Polystyrene), PVC (Polyvinyl Chloride), PE (Polyethylene), PET (Polyethylene Terephthalate), and ABS (Acrylonitrile Butadiene Styrene). It is also free of heavy metals, phthalates, and BPA (Bisphenol A), and is safely incinerable or compostable, releasing only H_2O and CO_2 without emitting toxic gases. By replacing petroleum-based polymers with environmentally friendly biodegradable materials, the proposed system not only reduces greenhouse gas emissions but also aligns with the global shift toward eco-friendly healthcare solutions, specifically Taiwan's 2032 national target of reducing carbon by 32% ± 2%. High caregiver satisfaction ratings point towards high acceptance potential in clinic and home settings. However, mass deployment will require additional validation in other care settings and extended operation times. Future integration with artificial intelligence (AI) and Internet of Things (IoT) analytics can evolve the proposed system from a reactive to a predictive healthcare platform, where it can identify abnormal patterns of excretion or early symptoms of gastrointestinal illnesses.

In summary, the study verifies both the technical feasibility and the practical utility of the smart fecal collection system. It reinforces the growing importance of gerontechnological innovation in improving human dignity, reducing caregiver stress, and promoting environmental stewardship within modern healthcare frameworks.

Limitations

While with favorable findings, this study has several limitations. First, although the ammonia sensor demonstrated rapid detection at 1 ppm in 60 seconds, precise quantification of individual gas components remains challenging due to the cross-sensitivity inherent in MOS technology. Even though the proposed system is designed to rely on the overall odor profile pattern rather than the concentration of a single gas, the fluctuations in fecal gas composition under varying physiological and environmental conditions may still affect detection precision. Secondly, only 30 caregivers were recruited for the pilot usability study, limiting the statistical generalizability of the findings. Furthermore, the limited communication range of BLE (Bluetooth Low Energy) may not be able to accommodate larger medical institutions. Finally, while the prototype of the proposed system demonstrates feasibility, further work is required to optimize large-scale production, ensure long-term stability, and validate the cost-effectiveness. Overcoming these challenges will be critical to achieving stable performance and widespread adoption in different care environments.

Plan for future implementation and system enhancement

A structured implementation roadmap has been developed to facilitate future large-scale deployment of the system. The next phase will involve clinical trials in multi-center hospitals and long-term care facilities to determine clinical reliability, durability, and user compliance under real-world conditions. Future work also includes securing intellectual property rights to facilitate technology transfer. While patents for the proposed system have been granted in Taiwan, there are pending applications in the United States under the title "Intelligent Gas-Sensing Fecal Collection Bag". These measures aim to obtain international commercialization rights and technological exclusivity. In addition, drawing on recent European research by Tanweer (2025) regarding eco-friendly sensor nodes for smart diapers, similar sustainable electronic solutions may be integrated into the proposed system to minimize e-waste and further enhance sustainability. Industrial partnerships will be established to optimize manufacturing processes. The production of biodegradable products using GCM technology will be managed by assistive device manufacturers, and data connectivity and cloud monitoring will be handled by IoT specialists.

Inspired by previous smart diaper studies in Europe, an IT infrastructure upgrade framework has been outlined. This modernization includes the use of edge devices, cloud computing, and AI analytics to enable real-time monitoring and event prediction. The "hardware, edge, cloud, software" architecture supports faster responsiveness, dependability, and more personalized medical care through data-driven recommendations. Concurrently, by utilizing machine learning to interpret patient defecation patterns, the future system is envisioned to generate personalized alerts and early warnings for intestinal abnormalities or diseases. Integration with the Taiwan government's long-term care reimbursement programs will further improve public accessibility and sustainability.

Conclusions

This study presents a smart fecal collection system equipped with real-time ammonia detection, wireless transmission, and eco-friendly materials. The proposed system showed high sensitivity, operational stability, and high caregiver acceptance while dramatically reducing carbon emissions. With its focus on both health care technology and sustainability, the smart fecal collection system presents a new paradigm in dignified and sustainable senior care. Through continuous validation, international patenting, and industrial partnership, the technology shows significant potential for clinical translation and large-scale deployment in future healthcare systems.

Acknowledgements

This work was supported by a grant from the Kaohsiung Medical University Hospital (grant numbers: KMUH-113-3R-68, SI11418) Kaohsiung Medical University (KT113P008) and National Science and Technology Council (NSTC:111-3114-8-037-002-,113-2314-B-037-081-, 114-2314-B-037 -068 -)

Note:

A preliminary version of this paper was presented at the 2025 ISG Student Paper Competition (Taiwan Selection) on 5 Sep 2025, in Kaohsiung City, Taiwan.

References

Brewster, E. T., Rounsefell, B., Lin, F., Clarke, W., & O'Brien, K. R. (2022). Adult incontinence products are a larger and faster growing waste issue than disposable infant nappies (diapers) in Australia. Waste Management, 152, 30-37.

Department for Environment, Food and Rural Affairs. (2023). Life cycle assessment of disposable and reusable nappies in the UK 2023 (Project Reference EV0493). https://randd.defra.gov.uk/ProjectDetails?ProjectId=20622

Muthu, S. S., Ng, F. S. F., Li, Y., Hui, P. C. L., & Guo, Y. (2013). Carbon and eco-footprints of adult incontinence products. Fibers and Polymers, 14(10), 1776–1781. https://doi.org/10.1007/s12221-013-1776-x

Machín, A., Cotto, M., Duconge, J., Morant, C., Petrescu, F. I., & Márquez, F. (2023). Sensitive and reversible ammonia gas sensor based on single-walled carbon nanotubes. Chemosensors, 11(4), 247.

Carusone, T. C., Shekhar, S., Frans, Y., Chen, W. Z., Toifl, T., Nagatani, M., ... & Redman-White, W. (2021, February). F6: Optical and Electrical Transceivers for 400GbE and Beyond. In 2021 IEEE International Solid-State Circuits Conference (ISSCC) (Vol. 64, pp. 533-536). IEEE.

imec. (2023). Smart diapers: Realizing smart diapers for the elderly that generate an alert when changing is required. https://www.imec-int.com/en/what-we-offer/research-portfolio/smart-diapers

Sethupathi, M., Khumalo, M. V., Skosana, S. J., & Muniyasamy, S. (2024). Recent developments of pineapple leaf fiber (PALF) utilization in the polymer composites—a review. Separations, 11(8), 245.

Tanweer, M. (2025). Eco-friendly disposable sensor node for smart diaper applications.

Gardner, J. W., & Bartlett, P. N. (1999). Electronic noses: Principles and applications. Sensors and Actuators B: Chemical, 18–19, 211–220.

Gomes, N. O., Paschoalin, R. T., Bilatto, S., Sorigotti, A. R., Farinas, C. S., Mattoso, L. H. C., ... & Raymundo-Pereira, P. A. (2023). Flexible, bifunctional sensing platform made with biodegradable mats for detecting glucose in urine. ACS Sustainable Chemistry & Engineering, 11(6), 2209-2218.