Smart Pellet System: Autonomous Colorimetric Diagnostics in Unprocessed Biological Waste for Low-Resource and Space Environments

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Abstract

By 2050, cancer is projected to reach 35 million new cases annually and cardiovascular disease to cause 35.6 million deaths per year, while up to 40% of people with diabetes develop chronic kidney disease. Yet early kidney damage frequently goes undetected, and, to our knowledge, no existing approach enables effortless early detection in remote areas and non-terrestrial environments with the simplicity and low cost we offer.

We propose Smart Pellet, a conceptual system of seven colorimetric pellets (3–5 mm), each targeting a single condition in unprocessed toilet water: albumin, fecal hemoglobin, NMP22, the pancreatic cancer biomarkers LYVE1 and REG1B, bilirubin, nitrite, and Helicobacter pylori antigen. Each pellet integrates up to six layers: an iron oxide pigment coating, an L-aptamer gate, an organosilica shell, a molecularly imprinted polymer layer, enzyme–nanozyme amplification, and chromogenic domains. We also propose a cistern-mounted device that distributes the pellets over a weekly cycle, together with two further configurations: one for space (urinary calcium and NT-proBNP) and one for chronic disease (a graded albumin pellet). This work establishes a scientific foundation for a passive, continuous, multi-disease health-monitoring platform applicable to resource-limited terrestrial communities and to future long-duration space exploration missions.

Keywords

Smart Pellet System; Smart Pellet Dispenser; Smart Toilet; Colorimetric Detection; Aptamer Biosensor; Nanozyme Diagnostics; Molecularly Imprinted Polymers; Point-of-Care Diagnostics; Chronic Kidney Disease; Early Detection; Space Medicine; Low-Resource Settings.

1. Introduction

By 2050, cancer is projected to reach 35 million new cases per year, a 77% increase over 2022, with the steepest proportional rise in low human-development countries; cardiovascular disease is projected to cause 35.6 million deaths annually, up from 20.5 million in 2025. Chronic kidney disease already affected an estimated 788 million adults in 2023, and up to 40% of people with diabetes develop it. Many of these conditions progress silently, and early detection improves outcomes, yet it depends on access to testing that remote and resource-limited settings, and future space habitats, cannot provide.

Existing diagnostic approaches remain dependent on conditions these environments cannot meet: separated biological samples, controlled reagent introduction, calibrated instrumentation, refrigerated storage of reagents, and trained personnel. In microgravity, the capillary and hydrostatic forces on which lateral-flow and microfluidic platforms depend are also absent. Moreover, to our knowledge, no existing approach tells a person, without any user intervention, that a particular color means going to a hospital.

We propose Smart Pellet, a conceptual system of seven colorimetric pellets (3–5 mm), each targeting a single condition in unprocessed toilet water: albumin, fecal hemoglobin, NMP22, the pancreatic cancer biomarkers LYVE1 and REG1B, bilirubin, nitrite, and Helicobacter pylori antigen. Each pellet integrates up to six layers, from an iron oxide pigment coating to chromogenic domains. A cistern-mounted device releases one pellet type per 24 hours over a weekly cycle, delivering a fresh pellet at each new user's first flush and plain water at the second, so that each pellet contacts water only during its test window. We further propose a space configuration and a chronic-disease configuration within the same framework. Because sensing is diffusion-driven, it does not depend on gravity.

The contributions of this work are:

* A conceptual seven-pellet system with a six-layer architecture, each pellet targeting one condition.
* A dispenser concept with a weekly cycle and a fresh pellet for each new user.
* A space configuration (urinary calcium and NT-proBNP).

* A chronic-disease configuration (a graded albumin pellet).

* A gravity-independent, diffusion-driven sensing principle.

Each pellet color corresponds to a specific condition, so that a color change directs the person toward medical evaluation for that condition.

Part I: Pellet System

2. Theoretical Framework

2.1 Model Assumptions

The analysis assumes a spherical pellet (3–5 mm; core 2–4 mm) immersed in toilet water at about 25 °C. Transport is by diffusion only, with no convection from flushing or mixing; the biomarker concentration at the pellet surface equals the post-dilution bulk concentration, which the pellet does not deplete; and fouling and nonspecific adsorption are neglected. Pathological concentration ranges, clinical thresholds and reported detection limits are literature-based values given for comparison, whereas the pellet-specific parameters (α_aptamer, α_tortuosity, K_m, V_max and the response times) are model estimates to be determined experimentally.

2.2 Diffusion Modeling — Fick's Second Law

Biomarker transport from toilet water through the aptamer-gated nanoporous shell and MIP layer to the biochemical core is modeled using Fick's second law with a biomarker consumption sink term:

$$\partial C/\partial t = D_{eff} \cdot \nabla^2 C - R(C)$$

where C is the local biomarker concentration (µM), t is time (s), D_eff is the effective diffusion coefficient corrected for mesopore tortuosity and aptamer gate resistance, and R(C) is the biomarker consumption rate. The effective diffusion coefficient is:

$$D_{eff} = \alpha_{aptamer} \cdot \alpha_{tortuosity} \cdot D_{bulk}$$

where D_bulk is the diffusion coefficient of the biomarker in water, α_aptamer (0.001–0.01) accounts for aptamer gate resistance in the open conformation and α_tortuosity (0.01–0.10) represents the mesopore tortuosity correction. For pellets without an aptamer gate (nitrite), α_aptamer = 1. D_bulk was estimated from the hydrodynamic radius of each biomarker: about 1.9×10■■ m²/s for nitrite, 4×10■¹■ m²/s for bilirubin and 5–9×10■¹¹ m²/s for the protein biomarkers. Numerical solution predicts biomarker transit times of 3–12 minutes for small-molecule biomarkers (bilirubin) and 8–18 minutes for macromolecular biomarkers (albumin, hemoglobin, NMP22) under pathological post-dilution concentrations; nitrite is assigned to the small-molecule class, and LYVE1, REG1B and H. pylori antigen to the macromolecular class.

2.3 Reaction Kinetics — Michaelis–Menten Model

Enzymatic reaction rates within each chromogenic microdomain are modeled using the Michaelis–Menten equation:

$$R(C) = (V_{max} \cdot C) / (K_m + C)$$

where V_max is the maximum reaction velocity (µM·s■¹), K_m is the Michaelis constant (µM), and C is the local substrate concentration. The combined enzyme–nanozyme system is predicted to generate visually detectable chromophore concentrations exceeding the ΔE = 2.3 CIELAB just-noticeable-difference threshold within 3–18 minutes across all seven pellets, assuming for the pancreatic cancer and H. pylori pellets the response time of the NMP22 immunoassay, and for nitrite the reading times of dipstick protocols.

The hemoglobin pellet (Hb-peroxidase mimic) has K_m = 0.5 µM and V_max = 0.20 µM·s■¹, and the bilirubin pellet (bilirubin oxidase) has K_m = 12 µM and V_max = 0.05 µM·s■¹. Albumin detection (Coomassie G-250 dye-binding) and nitrite detection (Griess reaction) are stoichiometric, and the NMP22, pancreatic cancer (LYVE1 + REG1B) and H. pylori pellets rely on sandwich immunoassays with an HRP-type reporter (immunoreaction), so Michaelis–Menten parameters do not apply. Predicted response times are 5–10 min (albumin), 3–6 min (hemoglobin), 10–18 min (NMP22, with the same range assumed for the pancreatic cancer and H. pylori pellets), 5–12 min (bilirubin) and 1–5 min (nitrite).

2.4 Dilution-Corrected Limit of Detection Analysis

Assuming a standard single void of urine or feces diluted in toilet water (27-fold dilution for urine), the following analysis quantifies post-dilution biomarker concentrations against theoretical limit-of-detection (LOD) values derived from the $\Delta E = 2.3$ CIELAB color threshold. A biomarker is classified as detectable when post-dilution concentrations exceed the LOD across most of the pathological range, and as marginal when the pathological range overlaps the LOD.

* Albumin: pathological concentration 30–300 mg/L becomes 1.1–11.1 mg/L (LOD <1 mg/L; clinical threshold >30 mg/L, CKD); detectable.

* Fecal hemoglobin: 50–500 µg/g (variable dilution) becomes 0.9–9.2 µg/mL (LOD 0.5 µg/mL; clinical threshold >10 µg/mL, CRC); detectable.

* NMP22: 10–100 µg/L becomes 0.4–3.7 µg/L (LOD <0.5 µg/L; clinical threshold >10 µg/L, bladder cancer); detectable.

* Pancreatic cancer (LYVE1 + REG1B): the corresponding sandwich ELISAs report detection limits of 8.19 pg/mL (LYVE1) and 3.13 pg/mL (REG1B); the post-dilution urinary concentrations are to be determined.

* Bilirubin: 50–200 µM becomes 1.8–7.4 µM (LOD 1–10 µM; clinical threshold >17 µM); marginal.

* Nitrite: the dipstick threshold of about 0.06 mg/dL (≈13 µM) becomes 0.5 µM, below a reported Griess LOD of 1.6 µM, so only samples above about 43 µM would be detectable.

* H. pylori: a stool-antigen cut-off of 20 ng/mL in extract corresponds to about 9 ng/mL, assuming complete suspension of a standard fecal mass in toilet water, which is 1.5–3.6 times the reported ELISA LODs of 2.5–5.9 ng/mL; detectable under complete suspension, and proportionally less otherwise.

The 27-fold dilution is an assumption. In practice it depends on bowl geometry, flush volume, residual water, urine volume and fecal load, and may vary by about an order of magnitude. All post-dilution values above scale inversely with the dilution factor; for example, the nitrite threshold of ≈13 µM would exceed its Griess LOD of 1.6 µM only at dilutions below ≈8-fold. Experimental verification is therefore required.

CKD = chronic kidney disease; CRC = colorectal cancer.

2.5 Dimensional Consistency

Order-of-magnitude transit times follow $\tau \approx L^2/D_{eff}$. For transit within 12–18 min, shell thickness is limited to ≈0.7–10 µm for the gated protein biomarkers and ≈2–17 µm for bilirubin, whereas the ungated nitrite pellet tolerates ≈0.1–0.4 mm. Because radial equilibration of a 2–4 mm core is slower than the test window ($\tau \approx R^2/\pi^2 D_{core} \approx$ 1–4 h for albumin, with $D_{core} \approx \frac{1}{2} D_{bulk}$), the catalytic and chromogenic components must be confined to an outer reactive layer of ≈160–220 µm for the protein biomarkers, ≈380 µm for bilirubin and ≈0.8 mm for nitrite. As the α ranges span two orders of magnitude, transit through a 2 µm shell varies from ≈1 to 110 min for albumin, and α must therefore be determined experimentally.

3. System Design

3.1 Pellet Architecture

The Smart Pellet System comprises seven pellet types, each a 3–5 mm spherical microreactor built from up to six functional layers:

1. An external iron oxide pigment coating for color identification and optical recognition by the dispenser.

2. An L-aptamer gate for selective entry of the target.

3. A nanoporous organosilica shell for size exclusion and structural support.

4. A molecularly imprinted polymer (MIP) layer for target recognition and concentration.

5. A biochemical core providing enzyme–nanozyme amplification.

6. Chromogenic microdomains for signal generation.

All pellets share this organization and differ in their target-specific components: the L-aptamer sequence, the recognition element, the immobilized enzymes and the chromogenic substrate. Layers that a pellet's detection chemistry does not require are omitted (Table 1).

Table 1. The seven pellet types

The external pigment color matches the internal color output. Pore sizes are set per target from its hydrodynamic dimensions.

Pellet Target biomarker Color Pigment Associated condition Layers Pore size

Pellet 1 Albumin Blue Prussian blue Kidney and vascular damage 1, 2, 3, 6 15–20 nm

Pellet 2 Fecal hemoglobin Red Iron oxide red Colorectal cancer 1–6 12–16 nm

Pellet 3 NMP22 Green Chromium oxide green Bladder cancer 1, 2, 3, 5, 6 15–20 nm

Pellet 4 LYVE1 + REG1B Purple Manganese violet Pancreatic cancer 1, 2, 3, 5, 6 10–14 nm

Pellet 5 Bilirubin Yellow Iron oxide yellow Hepatobiliary disorders 1–6 5–8 nm

Pellet 6 Nitrite Orange Iron oxide orange Urinary tract infection 1, 3, 6 5–8 nm

Pellet 7 H. pylori antigen Brown Iron oxide brown Gastric infection 1, 2, 3, 5, 6 15–20 nm

3.2 Layers

Layer 1: Pigment coating. Each pigment is dispersed in a dilute TEOS sol (2% v/v in ethanol, 5–10 mg/mL) and applied by a single dip-coating cycle, followed by thermal consolidation at 50 °C, forming a conformal 1–2 µm layer. The iron oxide pigments are approved by the FDA and EFSA for pharmaceutical coatings.

Layer 2: L-aptamer gate. L-aptamers (Spiegelmers), composed of L-configured nucleotides, are not recognized by nucleases. To bind a natural target, each sequence is obtained by mirror-image selection against the enantiomeric target. The aptamers are immobilized covalently by NHS–EDC coupling on the APTES-functionalized shell (amine density 2–4 µmol/m²). In the absence of the target, the closed-gate probability exceeds 0.98; at concentrations above the aptamer K_d, the open-gate probability exceeds 0.95.

Layer 3: Organosilica shell. The shell is a Pluronic P123-templated organosilica synthesized from TEOS (8 mL) and MTES (2 mL) in water (120 mL) and ethanol (10 mL) with P123 (4 g) at pH 2.0, aged at 35 °C for 24 h, cured at 80 °C for 24 h and freed of template by Soxhlet ethanol extraction. Pore diameter is set for each pellet, which maximizes target flux while excluding viral particles and bacterial cells. The shell thickness is limited by the transit-time constraints of Section 2.5: about 0.7–10 µm for the gated protein pellets, 2–17 µm for bilirubin and 0.1–0.4 mm for nitrite.

Layer 4: MIP layer. Used only by the fecal hemoglobin and bilirubin pellets. It is a polyacrylamide-based MIP crosslinked with N,N′-methylenebisacrylamide (20 mol%) and polymerized under UV initiation, using the hemoglobin β-chain peptide and bilirubin as templates. Binding affinities are 10–500 nM for small molecules and 1–50 nM for protein targets. It forms a 50–100 µm conformal coating between the shell and the core.

Layer 5: Biochemical core. The core is a gelatin hydrogel–silica hybrid (gelatin 5% w/v, silica sol 10% v/v, trehalose 5% w/v, PEG-400 10% v/v, in PBS pH 7.4). Trehalose protects the enzymes during dehydration–rehydration cycles. Enzymes are covalently immobilized by glutaraldehyde crosslinking (0.05% v/v, 30 min), with a retention above 95% during extended immersion. Fe■O■ (8–12 nm) and CeO■ (5–10 nm) nanozymes are dispersed by probe sonication (40 W, 5 min) and are predicted to leach less than 0.01 mg/L of Fe and Ce per use cycle.

Layer 6: Chromogenic microdomains. Each pellet carries a single population of PLGA microcapsules (20–50 µm) loaded with the chromogenic reagents of its own channel. They are confined to the outer reactive layer defined in Section 2.5.

3.3 Detection Chemistry

* Albumin: Coomassie G-250 dye-binding, a stoichiometric interaction (blue, λmax 595 nm).

* Fecal hemoglobin: anti-hemoglobin antibody fragments capture hemoglobin, which acts as a peroxidase mimic; AAP/phenol with H■O■ gives a quinoneimine (red, 505 nm).

* NMP22: sandwich immunoassay with anti-NMP22 capture antibody fragments and an HRP-conjugated detection antibody, with TMB as the chromogen (green, 620 nm). NMP22 (≈50 kDa, hydrodynamic diameter ≈5 nm) passes the 15–20 nm pores.

* Pancreatic cancer (LYVE1 + REG1B): sandwich immunoassays for the two proteins with an HRP-type reporter.

* Bilirubin: oxidation by bilirubin oxidase, with OPD yielding diaminophenazine (λmax 450 nm).

* Nitrite: Griess reaction, with dry reagents in layer 6.

* H. pylori antigen: sandwich immunoassay with an HRP-type reporter.

For the three new pellets, the chromogen that gives the pellet color is selected with the final design.

3.4 Assembly

The core matrix, loaded with immobilized enzymes, nanozymes and chromogenic microcapsules, is cast into 2–4 mm droplets with a coaxial microfluidic droplet generator and cured at 4 °C for 1 h. The MIP layer (50 nm MIP particles, 5 mg/mL in ethanol; 40 °C, 30 min) is applied only to the pellets that have it. The shell is dip-coated in TEOS/MTES sol and consolidated at 50 °C for 2 h; the L-aptamers are conjugated by NHS–EDC chemistry (2 h, room temperature, PBS pH 7.4); and the pigment is applied by a single dip-coating cycle in the pigment–silica sol, consolidated at 50 °C for 1 h. Steps for absent layers are omitted. The final diameter is 3–5 mm.

4. Part II: Space Configuration

4.1 Rationale

Long-duration spaceflight is associated with bone loss, an increased risk of kidney stones, which arises from dehydration and increased calcium excretion, and cardiovascular deconditioning. We propose a space configuration of two pellets that monitor urinary calcium and NT-proBNP. Because sensing is diffusion-driven, it does not depend on gravity.

4.2 Calcium Pellet

Calcium is present in urine at millimolar concentrations, so no amplification is needed. The pellet therefore uses only layers 1, 3 and 6; layers 2, 4 and 5 are omitted. The chromogenic dye is calcium-binding, and the external pigment is manganese violet (purple).

4.3 NT-proBNP Pellet

NT-proBNP, a marker of cardiac stress, has been reported to track plasma levels in urine and to be detectable in diluted urine by aptamer-based assays. The pellet uses layers 1, 2, 3, 5 and 6; layer 4 is omitted. The external pigment is Prussian blue (blue).

5. Part III: Chronic Disease Configuration

5.1 Rationale

People with diabetes, hypertension or chronic kidney disease are at risk of kidney and vascular damage; up to 40% of people with diabetes develop chronic kidney disease. Albumin in urine is an early indicator of such damage. This configuration provides a single albumin pellet, independent of the dispenser and of its seven-day program.

5.2 Albumin Pellet

The pellet is the albumin pellet of Part I (layers 1, 2, 3 and 6; Coomassie G-250 dye-binding) with a graded blue readout over 80–300 mg/L (3.0–11.1 mg/L after the 27-fold dilution of Section 2.4): the blue output deepens as albumin rises from 80 to 300 mg/L. Patients with chronic disease may be persistently positive, so the interpretation relies on the change from the individual's baseline across repeated tests.

6. Part IV: Smart Pellet Dispenser

6.1 Overview

The dispenser is a self-contained, cistern-mounted unit of five subsystems (Table 2), measuring 10 × 4 × 3 cm with a mass of about 30 g (34 g with a full cartridge). It is attached to the interior cistern wall with a silicone adhesive pad rated for continuous submersion and a secondary mechanical clip, and is compatible with cisterns whose internal dimensions exceed 25 × 15 × 30 cm.

Table 2. Subsystems of the dispenser

The dispenser consists of five main subsystems.

Subsystem Function Components and specifications

Pellet reservoir Provides dry storage of the pellets. Cylindrical channel measuring 8 mm in diameter by 160 mm in length, made of PETG with a sealed top cap.

Optical recognition subsystem Reads the pellet color before release. White LED combined with an RGB sensor (TCS34725) mounted on a waterproof-coated PCB.

Microprocessor Handles the release schedule and color logic. ATtiny85 running at 8 MHz with 8 KB of flash memory, implemented on a conformal-coated PCB.

Release mechanism Releases one pellet at a time. Hydraulic piston and ratchet wheel fabricated from POM with a silicone seal.

Housing Provides mounting and protection. 10 × 4 × 3 cm enclosure made of polypropylene and sealed with silicone adhesive.

6.2 Release Logic

The dispenser releases one pellet type per 24-hour period and cycles through the seven types over a weekly cycle; an internal timer changes the scheduled type every 24 hours. Within each period, flushes alternate: the first flush (a new user entering) delivers clean water together with a fresh pellet, and the second flush (the user leaving) delivers water only. The alternation starts at the first flush after cartridge insertion. On a release flush, the hydraulic pressure sensor detects the flush (<100 ms), the LED illuminates the lead pellet and the sensor reads its RGB values (200 ms), the microprocessor classifies the pellet (<10 ms) and checks whether its type is scheduled (<1 ms), and the ratchet then advances to release the pellet (500 ms) before the device returns to low-power sleep. If the lead pellet is not of the scheduled type, the ratchet advances without release and the next pellet is read. This non-destructive sorting allows the cartridge to be loaded in any order.

6.3 Optical Recognition

The TCS34725 sensor operates under a co-mounted white LED (6500 K, 500 mcd), independent of cistern lighting. The microprocessor classifies each pellet by nearest-neighbor matching against reference RGB vectors determined at manufacture under the device's own illumination, with a classification threshold of $\Delta E < 15$; a self-calibration routine runs every 30 days and on cartridge replacement. The minimum inter-class distance between the seven pigment signatures must be verified for the present pigment set. The electronics are protected by a 25 µm parylene C conformal coating, a sealed chamber with an O-ring-sealed polypropylene partition, and a sapphire window (4 mm diameter, 1 mm thick) rated to 1 m of continuous submersion.

6.4 Hydraulic Release

The mechanism has to release exactly one pellet per release flush, require no external power for actuation and work at dynamic pressures of 0.1–1.0 bar. The kinetic energy of the flush drives a silicone piston (12 mm diameter, 8 mm stroke) through a 2 mm orifice; the piston advances a POM ratchet wheel (20 mm, 14 teeth, 4.5 mm pitch) by one tooth through a stainless steel push rod, positioning the lead pellet over a 5.5 mm aperture through which it falls into the cistern water. A spring-loaded pawl prevents backward motion, and a return spring (0.8 N/mm) resets the piston. Electrical energy is used only by the optical and processing steps, about 0.8 mAh per cycle, from a CR2032 cell.

6.5 Cartridge

The cartridge is a sealed PETG tube (8 mm internal diameter, 160 mm long) with a foil moisture barrier at both ends. Loading requires removing the foil seals and inserting the tube; no further user action is needed.

6.6 Materials and Safety

All materials in contact with cistern water meet NSF/ANSI Standard 61: polypropylene (housing), PETG (reservoir), POM (ratchet), silicone (seals and piston) and 316L stainless steel (push rod and spring), all free of BPA and phthalates. The battery sits in a hermetically sealed sub-compartment with dual O-ring seals and is replaceable without tools through a quarter-turn cap. Spent pellets present minimal environmental risk: the iron oxide and chromium oxide pigments are inert, and the nanozymes and enzymes are covalently immobilized in the core.

6.7 Role in the System

The dispenser performs three functions that the pellets cannot perform alone: dry storage of unused pellets, which preserves enzyme activity and gate integrity; optically guided release of exactly one scheduled pellet type per user, which provides weekly coverage of the seven conditions with no change in user behavior; and a physical interface for future

digital integration.

7. Discussion

7.1 Meaning and Applications

Smart Pellet is a passive, screening-oriented system. Its readout is an alert rather than a diagnosis: each pellet color corresponds to a condition, and a color change directs the person to medical evaluation without any user intervention beyond normal toilet use. The system is intended for remote and resource-limited settings, where laboratory testing is not available, and, through its space configuration, for spaceflight; the chronic-disease configuration serves people who already carry a risk of kidney and vascular damage.

7.2 Comparison with Existing Approaches

The four leading competitors are:

(i) the Stanford precision-health toilet;

(ii) Withings U-Scan;

(iii) Healthy.io's Minuteful Kidney; and

(iv) home urine test strips.

There is nothing in the world that lets a person in remote areas undergo a test without his awareness, before he does it himself.

7.3 User Experience

The device needs no button presses, no app interaction, no sample collection and no result interpretation by the user beyond reading the pellet color, and only cartridge replacement is required. This behavioral transparency is a deliberate design choice, because adherence to diagnostics falls as procedural complexity rises. As for the user experience, it is an experience with a color for the sake of health, and our goal is that it becomes a story the user tells in the future: that he discovered what would have harmed him.

8. Limitations

* No experimental validation. All values are theoretical; the pellet-specific parameters are estimates to be determined experimentally.

* Recognition in toilet water. Matrix interference from urine, feces, cleaning agents and pigments, and fouling of the pellet, are not modeled. Color readout is further affected by turbidity and by the color of the waste. L-aptamers require mirror-image selection for each target, which is difficult for large proteins, and MIPs perform less well for proteins.

* Dilution. The 27-fold dilution is an assumption that may vary by about an order of magnitude with bowl geometry, flush volume and fecal load.

* Marginal detectability. Bilirubin and H. pylori are marginal, and nitrite is detectable only in strong positives. Nitrite detection is also affected by short bladder retention time and by ascorbic acid.

* Specificity of the readout. Dye-binding with Coomassie responds to proteins generally and not to albumin alone. Hemoglobin and nitrite are not specific to a single condition.

* Pancreatic panel. The LYVE1 + REG1B panel is interpreted with urinary creatinine and age, which a passive pellet cannot supply, and its urinary concentrations after dilution remain to be determined.

* Color matching. An external color matching the internal output may reduce contrast between the baseline and positive states.

* Test window. The result must be visible before the second flush; response times of up to 18 min may exceed the time a user remains.

* Shell geometry. The shell thicknesses of Section 2.5 and the confinement of the reactive components to an outer layer require fabrication and verification.

* Dispenser. The alternation between release and water-only flushes is disturbed by a double flush or a flush without use. The hydraulic release must be characterized across cistern types and flush pressures, and the battery lifetime must be re-evaluated with the 24-hour timer and the release rule.

* Storage. Enzyme and aptamer stability in humid cistern conditions is not validated.

9. Future Work

Future work should proceed in the following order:

(i) a single-analyte pellet tested in synthetic urine, starting with the albumin pellet;

(ii) measurement of dilution in real toilets;

(iii) determination of the α parameters and the shell thickness;

(iv) validation of the L-aptamers by mirror-image selection and of the pancreatic panel concentrations; and

(v) bench tests of the dispenser, including release across flush systems.

Beyond this first generation, an imaging sensor, wireless transmission and smartphone-based analysis could extend the device toward longitudinal monitoring. In the future, a single pellet could diagnose several diseases. In addition, country-specific pellets could be developed for diseases prevalent in a particular country.

10. Conclusion

We have proposed Smart Pellet, a conceptual system of seven colorimetric pellets for unprocessed toilet water, a cistern-mounted dispenser that releases a fresh pellet to each new user, and two further configurations for space and for chronic disease. The system is theoretical; its principal uncertainties are the chemistry of the pellets in toilet water and the experimental values of its model parameters.

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