A colorimetric-based bioreporter for rapid genotoxicity monitoring using *Escherichia coli*

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**ABSTRACT:** Environmental contamination of genotoxic agents has been a concern due to their ability to cause cellular DNA damages or cancer. In this work, the bioreporter \(P_{\text{recA}}\lambda\text{acZ}\) was constructed based on *Escherichia coli* by fusing a promoter of a DNA damage response gene (\(\text{recA}\)) to a \(\beta\)-galactosidase reporter gene (\(\lambda\text{acZ}\)), which is called *E. coli-recA* bioreporter (EREC). For a reliable measurement, a level of the genotoxicity was normalized by bacterial cell respiration. Well-known genotoxic agents including sodium azide, 4-nitroquinoline 1-oxide and benzene were individually exposed to EREC in comparison with Ames test and commercial SOS-Chromotest™. The EREC was able to detect the genotoxic levels of all tested genotoxic agents, i.e. at 5, 31 and 1563 mg/L for sodium azide, 4-nitroquinoline 1-oxide and benzene, respectively, while the other two tests were unable to detect the genotoxicity of benzene even at lethal concentrations. A practical platform of genotoxic level detection was further developed based on EREC as freeze-dried cells on a microtiter plate. The freeze-dried EREC, kept at \(-20^\circ\text{C}\) for three months, was able to maintain cell survival of more than 97% and genotoxic sensitivity comparable to that of the freshly prepared cells. The freeze-dried EREC was also able to detect the genotoxicity of representative environmental-polluted pesticides including Chlorpyrifos, Profenofos and Cypermethrin at 25, 100 and 100 mg/L, respectively, and at the maximum residue limits permitted in agriculture commodity of pesticide mixtures thereof. In conclusion, the EREC can be further applied as a high-throughput genotoxicity screening of environmental pollutants either as individuals or combinations thereof.

**KEYWORDS:** bioreporter, freeze-dried bacteria, *Escherichia coli*, genotoxicity, pesticide

**INTRODUCTION**

Large quantities of hazardous wastes generated from industrial activities containing genotoxic agents pose a threat to humans due to the effects of cellular DNA damage, leading to mutation or cancer [1]. Bioassay is an alternative method to detect environmental pollutants using living prokaryotic or eukaryotic organisms. Among all of the organisms, the bacterial-based bioassay is receiving increasing attention due to its ability to be genetically-engineered for specific sensing, high sensitivity and selectivity, low cost, short time for measurement and faster growth rate than animals or plants [2].

Nowadays, one of the most widely recognized bacteria-based bioassays is the Salmonella mutagenicity assay or Ames test. For this test, *Salmonella typhimurium* strains TA98 and TA100, containing the *rfa* and *uvrB* mutation and R-factor plasmid pKM101, all of which could enhance the sensitivity of detection are widely used. *S. typhimurium* strains carry mutations in genes involved in histidine synthesis (*his*\(^-\)), thus these strains cannot produce histidine which is required for bacterial growth. When tested substance causes mutation or reverses mutation at the histidine point (*his*\(^+\)), the bacteria cell can grow on histidine-free medium [3, 4]. However, the disadvantage of this assay is the time-consuming process, requiring two days for incubation of agar plates under selective conditions. Moreover, a skilled operator and labor intensiveness based on plate incorporation test are required [5]. Another famous approach for genotoxicity detection is a recombinant bacterial bioreporter based on the activation of the bacterial SOS response involved in the DNA damage system. Several colorimetric assays for screening the genotoxicity of environmen-
tal pollutants have been developed; for example, the Rec-lac test [6], umu test [7] and the SOS-Chromotest [8]. In all of these tests, the SOS system is fused to $\beta$-galactosidase; lacZ is used as a reporter gene, and the chromogenic $\beta$-galactosidase activity is measured to determine genotoxicity. For the commercial SOS-Chromotest™ using Escherichia coli PQ37, the structural gene for $\beta$-galactosidase is placed under the control of the sfi promoter involved in cell division. The rfa and uvrA genes of this strain are modified to increase the sensitivity to genotoxicants [9]. Nevertheless, substantial time is required due to the overnight reconstitution of lyophilized bacteria and hours of the genotoxic test process. Additionally, the cost of SOS-Chromotest™ is considerably high at 300–600 US dollars per kit (Environmental Bio-Detection Products Inc).

The aim of this study is to develop a color-based bacterial bioreporter for genotoxicity detection, of which the efficacy is validated with Ames test for mutagenicity and commercial SOS-Chromotest™ for genotoxicity detection. In this work, the lacZ-based E. coli bioreporter under the control of recA promoter was constructed for the qualitative detection of the genotoxic compounds using visible color gradient and the quantitative analysis using spectrophotometry. E. coli was selected as a host since it is a model strain widely used for genetic modification. The recA gene was selected based on its role in homologous recombination, induction of the SOS response and the mutagenic repair of DNA. In addition, recA promoter offers the most dramatic and sensitive response compared with uvrA and alkA [10]. The dose response of $\beta$-galactosidase production was measured and used as an indicator of genotoxicity. Bacterial metabolic activity based on bacterial respiration was used to ensure the survivability of the cells from high chemical concentrations used, which might lead to an underestimation of $\beta$-galactosidase induction. For long-term preservation and transport for on-site uses, the bioreporter was developed as freeze-dried cells. By studying the effects of model pesticides as individuals and combinations of pesticide mixtures, the pesticide used in this study included carbendazim that is classified as unlikely to be hazard while carbaryl, cypermethrin, chlorpyrifos and profenofos are classified as a class II, moderately hazardous pesticide according to the World Health Organization (WHO). Chlorpyrifos, cypermethrin, carbendazim showed genotoxic potential in human tissues or cells and can induce chromosome aberrations [11, 12]. Profenofos has been reported to be genotoxic on freshwater snails [13]. This bioreporter is intended to be a rapid, simple and low-cost tool for genotoxicity detection for large number of test samples.

MATERIALS AND METHODS

Chemicals and media

All chemicals used were analytical-grade purchased from Sigma-Aldrich (USA) or Merck (Germany). Five commercial-grade pesticides including carbendazim (50% WP), profenofos (50% w/v), cypermethrin (35% w/v), carbaryl (85% WP) and chlorpyrifos (40% w/v) were purchased from a local distributor (Syngenta Crop Protection Co., Thailand). The stock solution was dissolved in ethanol, then diluted to the desired concentrations using 10% (v/v) DMSO.

The cultivation media was Luria-Bertani (LB) medium (pH 7.0). The resuspended or rehydrated medium was M9G medium (M9 minimal medium (per liter): Na$_2$HPO$_4$·12H$_2$O, 15.05 g; KH$_2$PO$_4$, 3 g; NaCl, 0.5 g; NH$_4$Cl, 1 g; MgSO$_4$, 1 mM; CaCl$_2$, 0.1 mM; and supplemented with 0.2% glucose). Agar was added for solid medium at 15 g/L.

Construction of EREC bioreporter

E. coli DH5$\alpha$ ($F^{-}$, $\phi$80lacZAM15, $\Delta$(lacZYA-argF)U169, deoR, recA1, endA1, hsdR17($r_{K}'$,$m_{K}'$), phoA, supE44, $\lambda^{-}$, thi-1, gyrA96, relA1) was used as a host strain for bioreporter construction in this study. E. coli K-12 MG1655 is a laboratory strain, and recA promoter from this strain was selected as a model. The recA promoter was amplified by polymerase chain reaction (PCR). This promoter segment was integrated into the HindIII and XbaI sites of promoterless pUClacZ plasmid adjacent to the lacZ gene to develop P$_{recA}$lacZ (Fig. S1). E. coli DH5$\alpha$ harboring this recombinant plasmid is called EREC bioreporter and used for genotoxicity detection.

Characterization of EREC bioreporter with toxic agents

E. coli EREC cells were grown aerobically in LB medium with 100 g/mL ampicillin at 37°C under 150 rpm of shaking until the exponential phase (OD$_{600} = 0.3–0.4$). An antibiotic, ampicillin, was added to maintain the recombinant vector during cell cultivation. The cultures were then centrifuged at 4500 × g and 4°C for 15 min and washed twice with 0.85% NaCl before resuspended in the same volume of M9G medium. One hundred µL of the suspended cells (the initial concentration of
bacterial cell was $1 \times 10^8$ CFU/mL was aliquoted into a microtiter plate (Nunc™ Microwell™) following an exposure to 100 µL of the tested chemical at various concentrations: sodium azide (positive control of Ames test), 4-nitroquinoline 1-oxide (positive control of SOS-Chromotest™) and benzene (known as a human carcinogen). After incubating at 37°C for 60 min, the substrate X-gal (1 mg/mL) was added, followed by 30 min of incubation for β-galactosidase production (BG), resulting in blue color. For bacterial respiration, 10 µL of 0.9 M ferricyanide was added to 100 µL of the cell suspension and incubated at 37°C for 60 min, after that 10 µL of 0.025 M FeCl$_3$ (pH 0.6) was added and mixed to form colorimetric product Prussian Blue (PB), resulting in green color [14]. The BG and the PB concentrations were measured by UV-visible plate reader (Multiscan GO, Thermo scientific) at 660 nm. BG is determined from the OD$_{560}$ produced by the non-induced cells and AB$_{induce}$ is that of cells induced with toxic agents. The induction factor was modified from SOS-Chromotest™, which is defined as the BG/PB ratio of the induced cells divided by the ratio of non-induce cells. If the induction factor $> 2.0$, the tested compound is classified as genotoxic [15]. The principles of the genotoxicity detection by β-galactosidase production and the bacterial respiration by PB production of the bioreporter are described in Supplementary material (Fig. S2).

**Ames test and SOS-Chromotest™**

The Ames test was performed using bacteria *Salmonella typhimurium* strain TA100 to determine the mutagenic activity of the chemicals [4]. The mutagenicity is determined by the ratio between Induced revertant colonies (IR) and the Natural revertant colonies (NR), with the ratio $> 2$ indicating the mutagenic potential.

For genotoxicity detection, the SOS-Chromotest™ (Environmental Bio-Detection Products Inc. (EBPI)) was performed according to the manufacturer’s procedures using bacteria *E. coli* PQ37 (sfi: lacZ) [8, 15]. β-galactosidase (BG) and alkaline phosphatase (AP) activities were assayed. The SOS induction factor is defined as the BG/AP ratio of the sample divided by the ratio of control (non-exposure cell). The test compound showing an SOS induction factor $> 2.0$ is classified as genotoxic.

**Freeze-drying of EREC bioreporter**

Cells were resuspended in M9G medium with 10% (w/v) dextrose as cryoprotectant. Initial cell concentration ($10^8$ CFU/mL) was determined using colony-forming unit (CFU) technique. The bacterial cultures were aliquoted into a microtiter plate (100 µL per well), then frozen at $-80$ °C overnight and lyophilized at $-51$ °C with a vacuum of 0.2 mBar pressure (Freeze Dryer, LABCONCO). After 5–6 h of freeze-drying, the lyophilized cells were sealed under vacuum in an aluminum foil bag and stored at different temperatures; room temperature (RT; 25°C), 4°C, 0°C or $-20$ °C for 3 months until use. After rehydration with 100 µL of M9G medium, the number of colonies forming units (CFU) for each sample was determined by serially diluting the sample and plating on LB agar. The plates were incubated for 24 h at 37°C. Viabilities were determined as bacterial respiration and genotoxicity induction factor when exposed to sodium azide at various concentrations.

**The freeze-dried EREC bioreporter tests with pesticides**

For the test, serial 2-fold dilutions of pesticides were prepared with 10% DMSO to the final concentrations ranging from 0.2 to 1000 mg/kg. In addition, the mixtures of pesticides at the MRLs level of each pesticide were investigated.

**Statistical analysis**

Each treatment was performed in triplicate, and the results were presented as means with the standard deviation of the data presented as error bars. Experimental data were statistically analyzed using one-way ANOVA by Dunnett’s multiple comparison test (GraphPad Prism version 5, GraphPad Software, La Jolla, California, USA) with $p < 0.05$ considered statically significant.

**RESULTS AND DISCUSSION**

**Construction of EREC bioreporter**

*E. coli* DH5α harboring plasmid P$_{rec}$lacz was successfully constructed. The ferricyanide-based bacterial respiration yielded the orange color when bacteria cells were completely inactivated as determined by CFU technique. Bacterial cell death led to an underestimation of β-galactosidase induction since it yielded low intensity of blue color (Fig. S3).
Accordingly, the orange color was used as a cutoff for further β-galactosidase-based genotoxicity determination, and the bacterial respiration of more than 20% is required to confirm a positive result. The genotoxic potential of a sample based on β-galactosidase production is also scaled by the survival of the cells, measured through the formation of PB, allowing for the calculation of the genotoxicity induction factor.

Response of EREC bioreporter to toxic agents
Sodium azide is the standard mutagen [16] while 4-nitroquinoline 1-oxide and benzene are reported as the human carcinogens [17]. The dose-dependent response of EREC to all toxic agents was observed (Fig. 1). Exposure to 5 mg/L of sodium azide, which is the minimum detectable genotoxic concentration, inhibited 50% of bacterial respiration (Fig. 1a). The EREC gave positive genotoxicity to sodium azide at 5 to 5000 mg/L. The result agreed with the previous report that 5000 mg/L of sodium azide was genotoxic to E. coli WP100 (uvrA−, recA−) [18]. In case of 4-nitroquinoline 1-oxide, the genotoxicity was detected when exposed to 31 mg/L, resulting in 50% inhibition of bacterial respiration (Fig. 1b). It should be noted that the positive genotoxicity limit of the bioreporter developed in this study was reasonable as it was still in the range reported in the other study, which varied from 10 to 10000 mg/L [19]. In addition, using different bacterial host cells and reporter systems, bioreporter offered varied genotoxicity detection levels [8, 20]. Compared with the other chemicals, the genotoxicity of benzene was detected at much higher concentration, i.e., 781 mg/L in which the bacterial respiration was reduced to 20% (Fig. 1c). Benzene has been reported to produce many types of genetic damages including chromosome aberrations and DNA double-strand breakage [21]. When cells are exposed to DNA damage, RecA protein is induced to attain much higher levels [22]. Jiang et al [23] reported that bioreporter DH5α lux (recA:luxCDABE), of which recA promoter was cloned from the marine bacterium Vibrio natriegens and fused to a luminescent reporter gene, could monitor the genotoxicity of benzene at 0.08 mg/L. The difference in detection limits may be due to the variations in the sources of recA gene, reporter gene and test conditions. It was found that the bioluminescent reporter gene showed 10- to 1000-fold higher assay sensitivity compared to the fluorescent protein [24]; however, its instability at tropical temperature (30–37°C) and the luminometer requirement become the limitations of the bioluminescent reporter gene. Therefore, the EREC in this study has offered high potential in applications for genotoxicity detection.

Validation of EREC bioreporter to Ames test and commercial SOS-Chromotest™
Sodium azide is the positive control of Ames test using S. typhimurium strain TA100 [25]. The exposure to more than 0.78 mg/L of sodium azide induces mutagenic activity with the revertant frequency ratio of more than 2.0. A decreased revertant frequency was observed with the increasing concentration of sodium azide, indicating the dose-dependent cytotoxicity effect on the strain. While 4-nitroquinoline 1-oxide was reported for its genotoxicity when tested with strain TA100 [14], this strain showed negative effect on benzene genotoxicity detection (Fig. S4) since the strain was killed by benzene due to the absence of the enzyme superoxide dismutase (SOD). In addition, oxidative stress due to the presence of benzene also induced DNA strand breaks, causing cytotoxic to strain. The more cytotoxic benzene offered in comparison to its mutagenic activity, the less its possibility to be detected by the Salmonella assay [26].

The commercial SOS-Chromotest™ is for genotoxic detection, based on DNA damage measured through the SOS-DNA repair system using engineered E. coli PQ37 (sft: lacZ). 4-nitroquinoline 1-oxide is the positive control of SOS-Chromotest™, showing the positive genotoxic at concentration ⩾ 0.06 to 1 mg/L with the SOS-induction factor more than 2.0. However, SOS-Chromotest™ gave a negative result for sodium azide and benzene (Fig. S5). The negative effect on benzene of SOS-Chromotest™ was still ambiguous [27]. Flegrova et al [28] reported that sodium azide was also negative under SOS-Chromotest™. However, the positive result with sodium azide was already obtained via the induction of a specific point mutation in the recA test and Vitotox test (SOS response promoter; recN fused with luxCDABE reporter gene).

The efficacy of constructed EREC was compared to the Ames test and SOS-Chromotest™, focusing on the mutagenicity/genotoxicity (Table 1). The result showed that the developed bioreporter could detect mutagenicity and genotoxicity of sodium azide and 4-nitroquinoline 1-oxide corresponding to the benchmark Ames test and commercial SOS-Chromotest™, respectively. The higher sensitivity of the Ames test and SOS-Chromotest™, compared to the developed bioreporter, is due to the fact that the Salmonella strain had the modifications to increase
Fig. 1 Bacterial respiration (line) and genotoxicity induction factor (bar) of the EREC bioreporter when exposed to (a) sodium azide, (b) 4-nitroquinoline 1-oxide and (c) benzene at 37 °C for 1 h. The control was performed in 10% DMSO with no tested chemical. The first concentration above the dash line was reported as the minimum genotoxic concentration. Data are shown as the mean ± SD, derived from at least three independent repeats, and the error bars represent the errors of the mean.

sensitivity to mutagens. The SOS-Chromotest™ bacterial strain also has modifications to increase sensitivity to genotoxicity including the altered DNA repair system, the modified outer membrane to increase permeability and the modified SOS promoter [29]. While EREC and SOS-Chromotest™ used the same concept by fusing SOS response promoter to lacZ reporter gene, these two tests gave different results due to different E. coli strains and promoter function. The recA used in EREC is a multifunctional gene that is related to genetic recombination, regulating genes response to DNA damage and involved in highly mutagenic DNA repair while sfi used in strain PQ37 of SOS-Chromotest™ is involved in cell division inhibition.

From the results, the developed bioreporter has the potential to detect the mutagenicity and genotoxicity of various chemicals, some of which even
show false negative in the traditional Ames test and SOS-Chromotest™. The developed bioreporter was a rapid test using 1.5 h assay time compared to that of the Ames test and SOS Chromotest™ using 3–5 days and 2–3.5 h, respectively. In addition, the developed bioreporter cost is comparatively less than SOS-Chromotest™ because the imported commercial products may include tax, transportation fee, packaging fee, knowledge fee, etc.

Freeze-dried EREC bioreporter

The storage temperature was varied in order to achieve optimal preservation of the viability and activity of EREC up to 3 months. Bioreporter had been dried and stored in the presence of 10% (w/v) dextrose as a cryoprotectant since sugar has been shown to protect both membrane and protein intact bacteria during freeze-drying [30]. The result showed that room temperature (RT, 25 °C) and 4 °C were not the suitable temperature due to the decreasing cell viability during storage time (Fig. 2). While the storage at 0 °C showed no significant decrease in cell viability up to 2 months, the best maintenance of cell survival during prolonged storage was obtained when cells were stored at −20 °C, of which cell viability remained more than 97% after 3 months. Similarly, the lyophilized E. coli strains for toxicity monitoring were stored up to several months at −20 °C [31].

The freeze-dried cells were rehydrated and tested for the activity of genotoxicity detection by exposing them to sodium azide. During 2-month storage at 4 °C and 0 °C, the activity remained comparable to that of fresh EREC bioreporter. The 3-month storage and freezing at −20 °C showed the highest activity compared to the non-storage

Fig. 2 Cell survival of freeze-dried bacteria stored at room temperature (RT, 25 °C), 4 °C, 0 °C and −20 °C up to 3 months compared to a non-storage freeze-dried cell. Each value presents the means ± SD, derived from at least three independent repeats, and the error bars represent the errors of the mean. In the same storage temperature, according to Dunnett’s multiple comparison test, significant differences at p < 0.05 levels over control (non-storage) are indicated by different letters.

Fig. 3 Genotoxicity induction factor of freeze-dried EREC bioreporter for: (a) 1-month storage, (b) 2-month storage and (c) 3-month storage, when stored at room temperature (RT, 25 °C), 4 °C, 0 °C and −20 °C compared to a non-storage freeze-dried cell. Cells were exposed to sodium azide at various concentrations (mg/L); control is non-exposure cell. Data are shown as the mean ± SD, derived from at least three independent repeats, and the error bars represent the errors of the mean.
Table 1 Genotoxicity response of developed EREC bioreporter compared with the standard method: Ames test and commercial SOS-Chromotest™.

| Condition | Ames test | SOS-Chromotest™ | EREC |
|-----------|-----------|-----------------|------|
| Bacteria  | S. typhimurium strain TA100 | E. coli PQ37 (sfi:lacZ) | E. coli DH5α (recA:lacZ) |
| Assay time | 3–5 days | 3–3.5 h | 1.5 h |
| Method | Plate count | Colorimetric | Colorimetric |
| Modified capabilities | uvrB mutation | uvrA mutation | tag mutation |
| rfa mutation | rfa mutation |

Genotoxicity level

- Sodium azidea: + (≥ 0.78 mg/L)
- 4-nitroquinoline 1-oxideb: + (0.15–5 mg/L)c
- Benzene: + (≥ 0.06 mg/L)
- Chlorpyrifos, profenofos and cypermethrin were genotoxic at 25, 100 and 100 mg/L, respectively (Fig. S6). Our results indicate that chlorpyrifos, profenofos and cypermethrin were genotoxic on EREC and are in agreement with the previous reports [34, 35].

MRLs are the maximum residue limits of a pesticide permitted in an agricultural commodity. At the MRL levels or below, there is no adverse health effect on human. Since chili is an important food ingredient and cash crop in Thailand, and various pesticides are widely used in the chili farm [36], the MRL levels of a pesticide residue permitted in Thai agricultural standard of dried pepper chili was used in this study. The MRL levels are as follows: chlorpyrifos = 20 mg/L, carbaryl = 2 mg/L, cypermethrin = 10 mg/L, profenofos = 20 mg/L and carbendazim = 20 mg/L. Using EREC bioreporter, exposure to an individual pesticide at the recommended MRLs level does not seem to pose any hazard (Fig. 4). Since pesticides always occur in mixtures with other pesticides, herein the toxicity of pesticide mixtures...
was also tested. Interestingly, the synergistic toxicity was detected from pesticide mixtures of four pesticides including carbendazim + carbaryl + cypermethrin + chlorpyrifos and carbendazim + carbaryl + cypermethrin + profenofos. This result suggested that mixed pesticides should be a concern due to their much higher toxicity, which is in agreement with the other reports on the synergistic effect of the pesticide combination [37, 38]. Moreover, the pesticides have been shown to induce oxidative stress by generating reactive oxygen species and genotoxic effects by the irreversible damage to various cell organs [39]. The cumulative toxicological impact of pesticide mixtures is of a particular concern for farmers and people involved in agricultural activities.

CONCLUSION

The developed colorimetric E. coli bioreporter in this study showed effective monitoring of genotoxicity in the model toxicants. The results could correlate well with the standard Ames test and SOS-Chromotest™; furthermore, the bioreporter can identify benzene as a genotoxic agent. The freeze-dried bioreporter was able to be efficiently used after appropriate storage for three months. Tested with the pesticides, the EREC did not indicate the genotoxicity of individual pesticides at MRL concentrations; however, the positive results were found in the combinations of tested pesticides at MRL levels, suggesting a concern on the synergistic effects of pesticide mixtures. This simple and easy-to-use bioreporter can essentially be applied for monitoring the toxicity of environmental contaminants where the convenient and high-throughput technique is required. For a practical deployment, more validations of the test kit with various chemicals will be essential. The easy and convenient result interpretation with mobile application could be developed. In addition, to further develop this test kit, the sensitivity of the bioreporter host can be improved by cell engineering.

Appendix A. Supplementary data

Supplementary data associated with this article can be found at http://dx.doi.org/10.2306/scienceasia1513-1874.2020.039.

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Appendix A. Supplementary data

Fig. S1  Schematic organization of plasmid in the *E. coli* EREC: *P*_{recA}lacz was constructed by fusing promoter *recA* into the *Hind*III and *Xba*I sites of a promoterless *pUC19* containing *lacz* gene and *Amp* (ampicillin resistance).

![Diagram of plasmid organization](image)

**Fig. S2** Principle of colorimetric bacterial bioreporter (a) *lacz*-based recombinant bacteria for genotoxicity detection. When cell exposed to toxicant shows the related effect to DNA damage, the promoter activated the downstream reporter gene coding protein, and after substrate addition, the signal occurred corresponding to the stress level. (b) Bacterial respiration using prussian blue (PB) as a colorimetric indicator. Ferricyanide is easily reduced by bacterial metabolism to ferrocyanide, and ferrocyanide reacts with ferric ion to form prussian blue or green color pigment. In the presence of a toxic agent, the bacterial metabolic activity is reduced or stopped, with a consequent decrease in the ferrocyanide reduction rate to prussian blue formation.

![Diagram of bioreporter principle](image)
**Fig. S3** (a) Color expression of bacterial respiration; (b) color expression of β-galactosidase production; and (c) comparison survivability based on cell respiration and colony forming unit. The cut off of cell alive and cell death was orange color or < 20% bacterial respiration. Cells were exposed to sodium azide at various concentration (mg/L) at 37 °C for 1 h. The data are the mean with standard deviation from at least three replicates.

**Fig. S4** Mutagenic result by the Ames test of *S. typhimurium* strain TA100 exposed to (a) sodium azide and (b) benzene. The first concentration above the dash line was reported as the minimum genotoxic concentration. Data are shown as the mean ± SD, derived from at least three independent repeats, and the error bars represent the errors of the mean.
Fig. S5 Cell survival rate (line) and SOS induction factor (bar) of SOS-Chromotest using *E. coli* PQ37 (*sfi:*lacZ) exposed to (a) 4-nitroquinoline 1-oxide, (b) sodium azide and (c) benzene. Control is non-exposure cell. A survival rate of 80% is required to confirm a positive result, and SOS induction factor $>2.0$ is classified as genotoxic. The first concentration above the dash line was reported as the minimum genotoxic concentration. Data are shown as the mean ± SD, derived from at least three independent repeats, and the error bars represent the errors of the mean.
Fig. S6  Bacterial respiration (line) and genotoxicity induction factor (bar) of the *E. coli* EREC when exposed to the pesticide at 37 °C for 1 h; (a) carbaryl, (b) carbendazim, (c) chlorpyrifos, (d) profenofos and (e) cypermethrin. The first concentration above the dash line was reported as the minimum genotoxic concentration. Induction factor > 2.0 indicates genotoxic potential. Data are shown as the mean ± SD, derived from at least three independent repeats, and the error bars represent the errors of the mean.