



OPEN ACCESS

EDITED BY

Sandrina A. Heleno,
Polytechnic Institute of Bragança (IPB),
Portugal

REVIEWED BY

Tuamelsan Gebre,
Addis Ababa Science and Technology
University, Ethiopia
Ardaning Nuriliani,
Gadjah Mada University, Indonesia

*CORRESPONDENCE

Kyung Won Kim
✉ kwkim@hallym.ac.kr

RECEIVED 25 October 2025

REVISED 22 December 2025

ACCEPTED 29 December 2025

PUBLISHED 12 January 2026

CITATION

Jun E, Kim S, Lim S, Jang C and
Kim KW (2026) Anti-obesity and
health-promoting effects of
shiitake-fermented black rice bran in
Caenorhabditis elegans.
Front. Sustain. Food Syst. 9:1732061.
doi: 10.3389/fsufs.2025.1732061

COPYRIGHT

© 2026 Jun, Kim, Lim, Jang and Kim. This is
an open-access article distributed under the
terms of the [Creative Commons Attribution
License \(CC BY\)](https://creativecommons.org/licenses/by/4.0/). The use, distribution or
reproduction in other forums is permitted,
provided the original author(s) and the
copyright owner(s) are credited and that the
original publication in this journal is cited, in
accordance with accepted academic
practice. No use, distribution or reproduction
is permitted which does not comply with
these terms.

Anti-obesity and health-promoting effects of shiitake-fermented black rice bran in *Caenorhabditis elegans*

Eunyoung Jun, Sangyeong Kim, Seonyu Lim, Chanmi Jang and
Kyung Won Kim*

Department of Life Science, Multidisciplinary Genome Institute, Hallym University, Chuncheon, Republic of Korea

The global rise in obesity has increased interest in natural anti-obesity agents. Black rice bran, a by-product of rice processing, is rich in polysaccharides and polyphenols, whose bioavailability can be enhanced through fermentation. In this study, we investigated the anti-obesity effects of polysaccharide-rich black rice bran fermented with Shiitake mushroom mycelium, using *Caenorhabditis elegans* as an *in vivo* model. The water-soluble fermentation culture supernatant was administered to worms fed a high-fat diet induced by oleic acid, and body fat accumulation was assessed using Oil Red O staining. Supplementation markedly reduced body fat accumulation without causing adverse physiological effects. Moreover, it mitigated age-related motility decline in liquid culture and attenuated the deterioration of intestinal barrier integrity during adulthood. Together, these results demonstrate that the fermented black rice bran supernatant not only suppresses lipid accumulation but also preserves key physiological functions associated with healthspan. These findings suggest that bioprocessed black rice bran is a safe, multifunctional ingredient with anti-obesity and healthy aging potential, highlighting its promise for metabolic health applications and its contribution to a sustainable food system through the valorization of food by-products.

KEYWORDS

aging, agricultural by-product, anti-obesity, black rice bran, fermentation, motility

Introduction

The global prevalence of obesity continues to rise, contributing to a growing burden of metabolic disorders such as type 2 diabetes, cardiovascular disease, and fatty liver (Bhupathiraju and Hu, 2016; Zhang et al., 2024). While pharmacological treatments exist, concerns over long-term safety and side effects have led to increasing interest in natural, food-derived materials as safer alternatives for obesity prevention and management (Zhao et al., 2024; Li et al., 2022).

Among these, agricultural by-products, also known as biowaste, have gained attention for their potential to be converted into functional bio-based products (Saravanan et al., 2023). Black rice (*Oryza sativa* L.) bran, a by-product of rice milling, is rich in bioactive compounds including anthocyanins, phenolic acids, and phytosterols, which have been associated with antioxidant, anti-inflammatory, and anti-obesity effects (Kwon et al., 2024; Ghasemzadeh et al., 2018; Ling et al., 2001; Limtrakul et al., 2015; Liu et al., 2020). However, despite its promising composition, black rice bran remains largely underutilized.

Fermentation is widely employed to enhance the bioavailability and biological activity of plant-derived materials. In particular, fermentation with *Lentinula edodes* (Shiitake mushroom)

mycelium has been reported to break down complex macromolecules such as proteins and phytic acid, enhance the release of phenolic compounds, improve digestibility, and generate antioxidant metabolites such as ergothioneine and water-soluble polysaccharide fragments (Tepwong et al., 2012; Clark et al., 2022). Notably, a comparative analysis of Shiitake-mycelium-fermented rice bran varieties demonstrated that black rice bran exhibits the greatest enhancement in phenolic content and antioxidant activity following fermentation, likely due to its anthocyanin-rich matrix (Jung et al., 2017). These findings suggest that black rice bran is particularly responsive to fermentation-driven release of bioactive compounds, providing a strong rationale for its use in the present study. When black rice bran undergoes this bioprocessing, the resulting supernatant obtained after removal of insoluble components (Black rice bran fermented with Shiitake mycelium-derived supernatant [BRB-F-S]; Figure 1A) is expected to contain elevated levels of soluble phenolic compounds as well as mycelium-derived metabolites.

Bioprocessed black rice bran has previously demonstrated antioxidant, anti-cancer, anti-hangover, and anti-allergic effects in rodent models (Kim et al., 2021; Kwon et al., 2023; Lee et al., 2023; Kim et al., 2013). Some studies have reported its anti-obesity effects in high-fat diet-fed rodents (Kwon et al., 2024). However, its influence

on physiological functions, particularly in the context of healthy aging, remains poorly understood.

In this study, we investigate the anti-obesity effects of BRB-F-S using a high-fat diet-induced *Caenorhabditis elegans* model. *C. elegans* is a well-established *in vivo* system for studying lipid metabolism, locomotion, and gut barrier function, making it suitable for evaluating both metabolic and functional outcomes (McKay et al., 2003; Ashrafi, 2007). It provides several advantages over rodent models, including rapid generation time, conserved lipid metabolic pathways, and scalable functional assays. Beyond measuring fat accumulation, we also assess age-related changes in motility and intestinal permeability to determine whether BRB-F-S not only reduces fat storage but also helps preserve physiological functions during aging. Although bioprocessed black rice bran has shown metabolic benefits in rodent studies, its effects on functional aging parameters and gut integrity have not been examined in any model. By integrating metabolic and aging-related readouts, our work provides the first *in vivo* evidence that BRB-F-S supports both fat reduction and maintenance of physiological health. This study suggests that bioprocessed black rice bran may serve as a safe, multifunctional natural ingredient for supporting metabolic health and contributing to the development of a more sustainable food system.

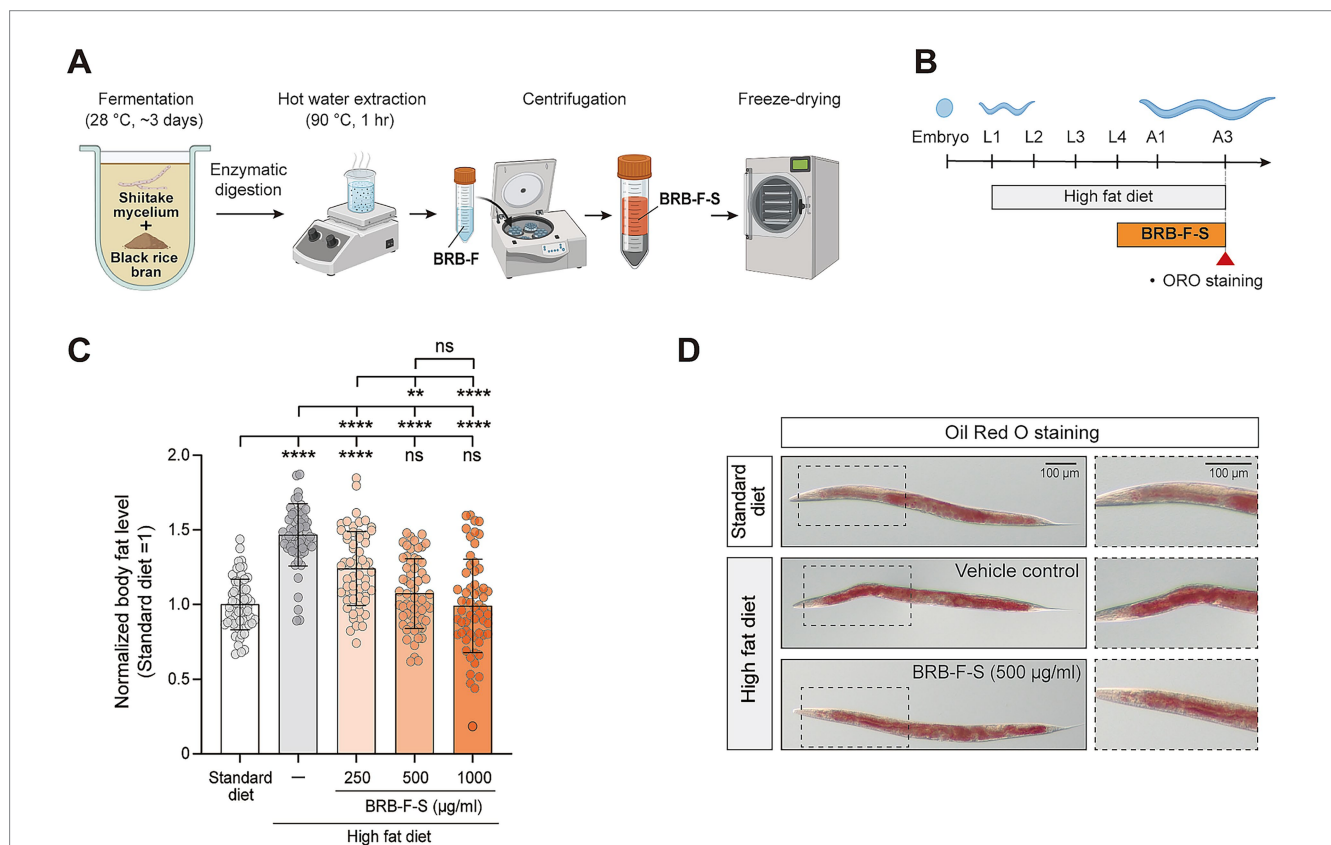


FIGURE 1
 Effects of BRB-F-S on body fat accumulation in *C. elegans*. **(A)** Schematic representation of BRB-F-S preparation. Created in BioRender. lab, R. (2025): <https://BioRender.com/pqaggs4>. **(B)** Schematic overview of Oil Red O (ORO) staining assay. Created in BioRender. lab, R. (2025): <https://BioRender.com/0xtcdb2>. **(C)** Quantification of body fat levels by ORO staining in day 3 adult worms under high-fat diet conditions (1 mM oleic acid), treated with BRB-F-S at 0, 250, 500, or 1,000 µg/mL. Values are normalized to the standard diet control (set as 1). Data represent mean ± SEM, with each dot indicating an individual worm ($n = 60$ worms per group, pooled from 3 independent experiments). Statistical significance was determined using one-way ANOVA followed by Tukey's *post hoc* test (** $p < 0.01$, **** $p < 0.0001$, ns = not significant). **(D)** Representative ORO-stained images of worms, with insets showing 1.5 × magnified views of the intestinal region to highlight differences in fat accumulation. Scale bar = 100 µm.

Materials and methods

Caenorhabditis elegans strains and maintenance

The wild-type *C. elegans* N2 strain (Brenner, 1974) obtained from the Caenorhabditis Genetics Center (CGC), which is funded by NIH Office of Research Infrastructure Programs (P40 OD010440) was maintained at 20 °C on Nematode Growth Medium (NGM; 51.3 mM NaCl, 2.5% (w/v) peptone, 2% (w/v) agar, 10 mg/L cholesterol, 1 mM CaCl₂, 1 mM MgSO₄, 25 mM KH₂PO₄) plates seeded with *Escherichia coli* OP50 as the food source (Brenner, 1974). To ensure consistent culture conditions and avoid overcrowding effects, worms were maintained on 60 mm NGM plates with a maximum of 100 worms per plate, while each experiment was conducted using approximately 30–50 worms per plate. High-fat diet conditions were achieved by supplementing NGM medium with 1 mM oleic acid (Han et al., 2017; Papsdorf et al., 2023). Oleic acid was dissolved in absolute ethanol to prepare a 50 mM stock solution, which was added to NGM medium to achieve a final concentration of 1 mM. The medium was subsequently autoclaved before pouring, during which ethanol is effectively removed. Fresh oleic acid stock solutions were prepared weekly, stored at 4 °C in the dark, and discarded after two weeks to minimize oxidation.

Synchronizing developmental stages of Caenorhabditis elegans

To synchronize the developmental stages of the nematodes, the embryos of the F1 generation were obtained by bleaching gravid adults. The embryos were washed four times with M9 buffer solution and cultured on NGM plates at 20 °C until they reached the first larval (L1) stage (Stiernagle, 2006).

Preparation and administration of BRB-F-S

The BRB-F-S compound was produced by STR Biotech (Chuncheon, Republic of Korea) using a previously described Shiitake-mycelium bioprocessing method (Kwon et al., 2024). In brief, black rice bran (100 g/L) was enzymatically pre-treated, fermented with *Lentinula edodes* mycelium under controlled temperature and agitation, and subjected to cell-wall-degrading enzyme treatment, hot-water extraction, and centrifugation to obtain the water-soluble fraction (BRB-F-S; Figure 1A). It was diluted in distilled water to a final concentration of 1,000 µg/mL and sterilized by filtration through a 0.2 µm filter. Each treatment solution was then mixed with an *E. coli* OP50 pellet and provided to nematodes as a food source.

High-fat diet induction and BRB-F-S treatment

To induce a high-fat condition, worms were exposed to oleic acid at a final concentration of 1 mM starting from the L1 stage. BRB-F-S was supplemented at final concentrations of 0, 250, 500, or 1,000 µg/mL. For BRB-F-S supplementation, approximately 30–50 L4 stage worms were used per condition and maintained on 60 mm NGM

plates. BRB-F-S treatments were initiated at the L4 stage and continued for the indicated durations (Figure 1B).

Oil Red O staining and lipid quantification

Worms were grown on NGM plates containing 1 mM oleic acid, and at the L4 stage, they were supplemented with 500 µg/mL BRB-F-S for 3 days. The Oil Red O staining was adapted from a previously described procedure (Wang and Ching, 2021). The worms were washed with 1 × PBST (1 × PBS containing 0.05% Triton X-100) and fixed in 600 µL of 60% isopropanol by shaking at room temperature for 1 h. After fixation, worms were stained overnight with 600 µL of a 60% Oil Red O solution (Sigma-Aldrich, cat# O1391). Following three washes with 1 × PBST, the worms were transferred to unseeded NGM plates for imaging.

Quantification of Oil Red O staining intensity was performed using the Python OpenCV library. The red channel of each image was extracted and converted to an 8-bit grayscale format. The body region of each worm was segmented by thresholding, and pixel intensity values (range: 0–255) within this region were summed to obtain the total staining intensity. To correct for variations in worm size, summed intensities were normalized to the theoretical maximum (worm area pixel count × 255). Normalized values from all samples were then expressed relative to the mean intensity of the control group, which was set to 1.

Thrashing assay

L4-stage worms were supplemented with 500 µg/mL BRB-F-S for 3, 5, or 7 days to obtain day 3, 5, and 7 adults, respectively, followed by washing and recovery in M9 buffer. As controls, age-matched worms maintained under identical conditions without BRB-F-S supplementation were used. The thrashing assay was adapted from a previously described procedure (Choi et al., 2025). For each assay, five worms were transferred into a 20 µL drop of M9 buffer and allowed to adapt for 1 min before recording. Thrashing, defined as a complete left–right C-shaped body bend, was quantified by manually counting the number of body bends over a 30-s interval while worms were freely swimming in M9 buffer under a stereomicroscope. The experiment was repeated three times per group (15 worms per condition).

Locomotion speed assay

L4-stage worms were supplemented with 500 µg/mL BRB-F-S for 3, 5, or 7 days to obtain day 3, 5, and 7 adults, respectively, under standard diet condition. As controls, age-matched worms maintained under identical conditions without BRB-F-S supplementation were used. Worms were washed three times with M9 buffer and transferred (10–20 worms per plate) onto unseeded 35-mm NGM plates for brief recovery. Locomotion was assessed using the WMicrotracker SMART ×8 system and its associated software (Phylumtech, Argentina). Worms were exposed to blue light stimulation for 10 s, followed by a 5-min video recording. The WMicrotracker SMART system tracked individual worms at 1 frame/s, and locomotor speed was calculated as

the total distance traveled divided by the number of seconds the worm was detected. For each plate, the average speed (mm/s) across all tracked worms were computed. Each experiment was independently repeated three times per condition.

Intestinal permeability (“blue-dye leakage”) assay

L4-stage worms were supplemented with 500 µg/mL BRB-F-S and cultured to day 3, 5, and 7 of adulthood under standard diet condition. As controls, age-matched worms maintained under identical conditions without BRB-F-S supplementation were used. Intestinal permeability assay was adapted from a previously described procedures (Jeong et al., 2024; Lee et al., 2022). Approximately 100 worms per condition were collected, washed with M9 buffer, and resuspended in 60 µL of M9 buffer. A staining solution was prepared by mixing FD&C Blue No.1 (Spectrum Chemical, cat# FD110) with an *E. coli* OP50 pellet suspension, at a ratio of 2:3. An equal volume (60 µL) of this staining solution was added to the worm suspension, yielding a final volume of 120 µL. The mixture was incubated at 20 °C for 2 h to allow dye ingestion. Worms were then washed three times with M9 and observed under a microscope. Intestinal permeability was assessed by microscopic examination: worms retaining blue dye within the intestinal lumen were scored as normal, whereas those showing whole-body or regional dye leakage were scored as having a leaky gut (Smurf-like) phenotype. At least 50 worms were examined per group, and each experiment was independently repeated three times.

Statistical analysis

All experiments were independently performed at least three times. Each figure legend indicates the number of animals analyzed (n) and the number of biological replicates. Data are presented as the mean or the mean ± standard error of the mean (SEM). Statistical analyses were performed using GraphPad Prism 10, with paired or unpaired t-tests, Chi-square tests, or one-way ANOVA applied as appropriate. The specific statistical test used is indicated in each figure legend. A *p*-value less than 0.05 was considered statistically significant.

Results and discussion

To evaluate the anti-obesity effects of BRB-F-S (Figure 1A), *C. elegans* were exposed to 1 mM oleic acid to induce a high-fat condition, as oleic acid promotes lipid droplet formation (Papsdorf et al., 2023; Han et al., 2017). Lipid accumulation was assessed by Oil Red O staining, which primarily detects neutral lipids such as triacylglycerides (O'Rourke et al., 2009) and is widely used as a reliable indicator of fat stores in *C. elegans*. This approach enabled direct visualization and quantitative comparison of lipid levels among groups. Worms were treated with BRB-F-S at 0, 250, 500, or 1,000 µg/mL under high-fat diet conditions (Figure 1B). Control worms were maintained under identical high-fat conditions without BRB-F-S supplementation, while additional control group was maintained under standard diet conditions without BRB-F-S. Lipid accumulation

was quantified by Oil Red O staining followed by automated pixel-intensity analysis. Treatment with BRB-F-S significantly reduced body fat accumulation in a dose-dependent manner (Figure 1C). Notably, this reduction was progressive with increasing concentrations, and at 500 µg/mL or higher, lipid levels decreased to those observed in worms fed a standard diet (Figure 1C), suggesting a strong restorative effect rather than a partial reduction. A marked reduction in staining intensity was particularly evident in the posterior pharyngeal region (Figure 1D), where fat typically accumulates in high-fat-fed animals, indicating a region-specific depletion pattern. These findings indicate that BRB-F-S exerts a notable *in vivo* fat-lowering effect. Comparable anti-obesity outcomes have been reported in rodent models, where BRB-F-S supplementation reduced white adipose tissue mass and blood triglyceride levels (Kwon et al., 2024), supporting the cross-species conservation of metabolic effects. A limitation of this study is the absence of biochemical lipid measurements, which will be addressed in future work.

To determine whether BRB-F-S affects physiological functions during aging, we examined its effects on locomotion and intestinal barrier integrity under standard diet conditions (Figure 2A). We used 500 µg/mL as the working concentration, as the dose-response curve in Figure 1C showed that lipid reduction reached a plateau at this dose. Motility was assessed using both liquid-based thrashing and solid-based body bending assays at days 3, 5, and 7 of adulthood. In the thrashing assay, BRB-F-S-treated worms maintained significantly higher locomotor activity at days 5 and 7 compared to untreated controls (Figure 2B), consistent with a delay in age-associated decline in neuromuscular function. In contrast, body bend speed on solid medium remained unchanged (Figure 2C), suggesting that the beneficial effects of BRB-F-S are more pronounced under conditions requiring continuous dynamic movement. Intestinal barrier integrity, evaluated using the intestinal permeability assay, showed differences between BRB-F-S-treated and control worms at days 3 and 7 (Figure 2D), with more pronounced effects in aged worms at day 7. These findings suggest that BRB-F-S helps maintain intestinal barrier function during aging, rather than compromising gut health, highlighting an important safety consideration for long-term dietary interventions.

Collectively, these findings show that BRB-F-S reduces fat accumulation without compromising key physiological parameters such as mobility or intestinal barrier function. The observed preservation of locomotor capacity and gut integrity further highlights BRB-F-S as a multifunctional agent that supports both metabolic and physiological health. Given these benefits and its natural origin, BRB-F-S holds promise as a safe dietary supplement and a candidate for development as a health-promoting ingredient. However, this study did not include an unfermented black rice bran extract or a blank fermentation control and the specific active metabolites responsible for these effects remain unidentified. Although the chemical profiling of BRB-F-S has not yet been performed, fermentation-released phenolic compounds and other antioxidant metabolites are likely to be enriched. Future compositional analyses will help clarify these mechanisms. Additionally, this study did not include molecular validations of lipid metabolism or antioxidant-related pathways, and therefore the underlying mechanisms remain to be fully elucidated. Importantly, as BRB-F-S is derived from the fermentation of an agricultural by-product, its newly identified functions not only add value to otherwise discarded materials but also

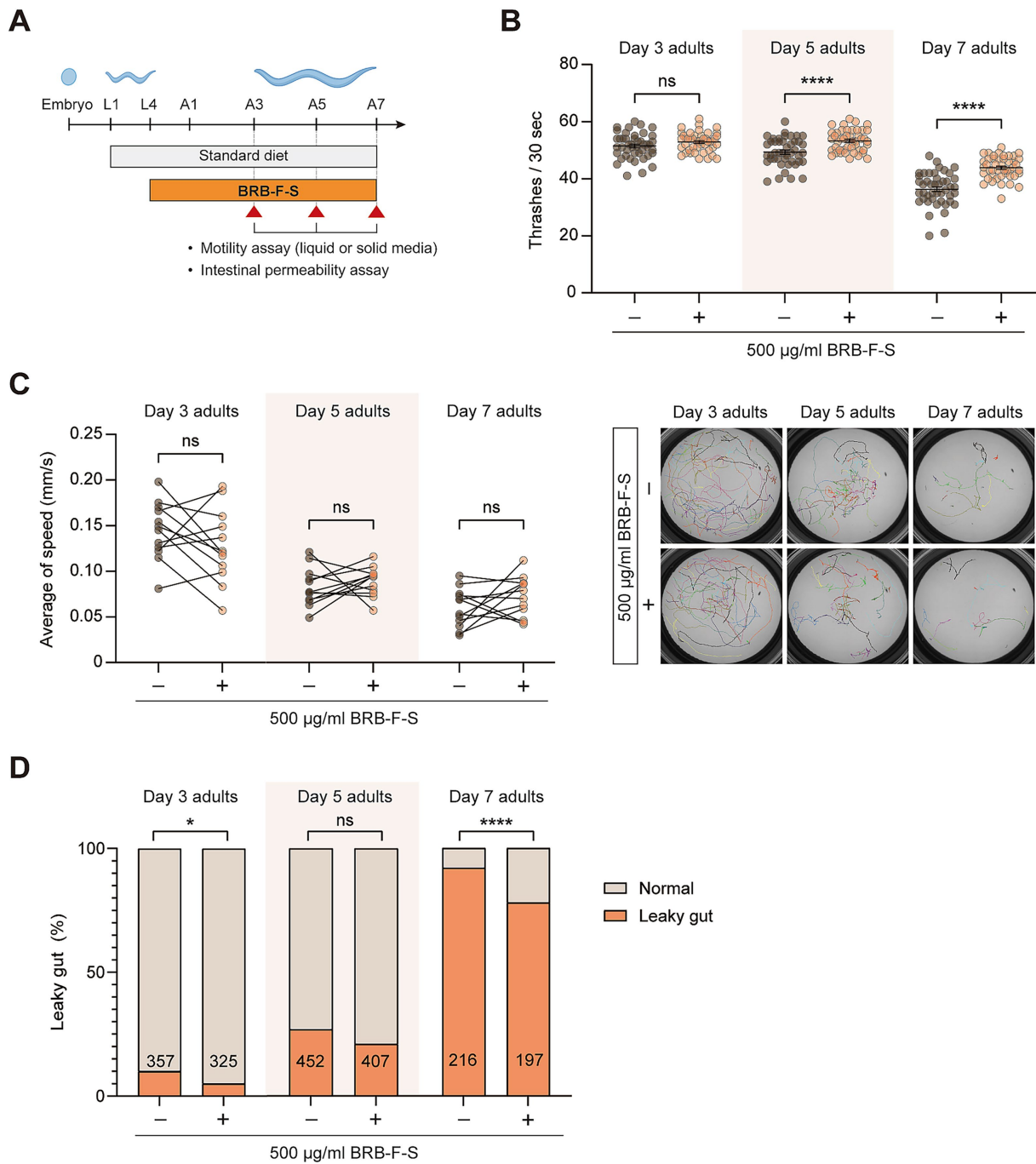


FIGURE 2

Effects of BRB-F-S on motility and intestinal barrier function in *C. elegans*. (A) Schematic overview of the motility and intestinal permeability assays. Created in BioRender. Lab, R. (2025): <https://BioRender.com/935adxi>. (B) Quantification of thrashing frequency in liquid medium on days 3, 5, and 7 of adulthood under standard diet conditions, with or without BRB-F-S supplementation (500 µg/mL). Thrashing frequency was quantified for each worm over a 30-s interval, with 15 worms analyzed per biological replicate. Data are represented as mean ± SEM, with each dot representing an individual worm ($n = 45$ worms per group, pooled from 3 independent experiments). Statistical significance was determined using an unpaired Student's *t*-test ($****p < 0.0001$, ns = not significant). (C) Locomotion on solid medium measured as average speed (mm/s) at days 3, 5, and 7 of adulthood. Four replicates were performed per group per trial ($n = 12$ per group, pooled from 3 independent experiments). Each dot denotes the average speed of 10–20 worms measured on a single plate, and each line indicates a paired comparison between control and BRB-F-S groups. Statistical significance was determined using a paired Student's *t*-test (ns = not significant). Representative locomotion tracks of *C. elegans* are shown on the right, with individual worm trajectories distinguished by different colors. (D) Percentage of worms exhibiting gut leakage on days 3, 5, and 7 of adulthood. Data are presented as percentages. Statistical significance was assessed using a two-tailed chi-square test ($*p < 0.05$, $****p < 0.0001$, ns = not significant). Gut leakage was assessed for each individual worm, with analyses pooled across 3 independent biological replicates; total sample sizes are indicated in the bars.

contribute to a more sustainable food system, aligning health promotion with environmental and societal sustainability.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

EJ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. SK: Investigation, Methodology, Visualization, Writing – original draft. SL: Investigation, Writing – original draft. CJ: Investigation, Writing – original draft. KK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was financially supported by the Hallym University Research Fund (HRF-202508-005).

References

- Ashrafi, K. (2007). Obesity and the regulation of fat metabolism. WormBook: the online review of *C. elegans*. Biology. doi: 10.1895/wormbook.1.130.1
- Bhupathiraju, S. N., and Hu, F. B. (2016). Epidemiology of obesity and diabetes and their cardiovascular complications. *Circ. Res.* 118, 1723–1735. doi: 10.1161/CIRCRESAHA.115.306825
- Brenner, S. (1974). The genetics of *Caenorhabditis elegans*. *Genetics* 77, 71–94. doi: 10.1093/genetics/77.1.71
- Choi, S., Jun, E., Lee, Y., and Kim, K. W. (2025). Exploring comprehensive toxic effects of fludioxonil on *Caenorhabditis elegans*. *Ecotoxicol. Environ. Saf.* 294:117996. doi: 10.1016/j.ecoenv.2025.117996
- Clark, A. J., Soni, B. K., Sharkey, B., Acree, T., Lavin, E., Bailey, H. M., et al. (2022). Shiitake mycelium fermentation improves digestibility, nutritional value, flavor and functionality of plant proteins. *LWT* 156:113065. doi: 10.1016/j.lwt.2021.113065
- Ghasemzadeh, A., Karbalaii, M. T., Jaafar, H. Z. E., and Rahmat, A. (2018). Phytochemical constituents, antioxidant activity, and antiproliferative properties of black, red, and brown rice bran. *Chem. Cent. J.* 12:17. doi: 10.1186/s13065-018-0382-9
- Han, S., Schroeder, E. A., Silva-Garcia, C. G., Hebestreit, K., Mair, W. B., and Brunet, A. (2017). Mono-unsaturated fatty acids link H3K4me3 modifiers to *C. elegans* lifespan. *Nature* 544, 185–190. doi: 10.1038/nature21686
- Jeong, A., Park, S. J., Lee, E. J., and Kim, K. W. (2024). Nanoplastics exacerbate Parkinson's disease symptoms in *C. Elegans* and human cells. *J. Hazard. Mater.* 465:133289. doi: 10.1016/j.jhazmat.2023.133289
- Jung, T.-D., Shin, G.-H., Kim, J.-M., Choi, S.-I., Lee, J.-H., Lee, S. J., et al. (2017). Comparative analysis of γ -oryzanol, β -glucan, total phenolic content and antioxidant

Acknowledgments

We thank the members of Kim's laboratory, as well as Sung Phil Kim and Sang Jong Lee at STR Biotech Co., Ltd., for their insightful discussions.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. Generative AI was used solely for the purpose of English language editing.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

activity in fermented rice bran of different varieties. *Nutrients* 9:571. doi: 10.3390/nu9060571

Kim, S. P., Lee, J. R., Kwon, K. S., Jang, Y. J., Kim, J., Yu, K. H., et al. (2021). A bioprocessed black rice bran glutathione-enriched yeast extract protects rats and mice against alcohol-induced hangovers. *Food Nutr. Sci.* 12:223. doi: 10.4236/fns.2021.123018

Kim, Y.-H., Lee, Y.-J., Park, S.-O., Lee, S.-J., and Lee, O.-H. (2013). Antioxidant compounds and antioxidant activities of fermented black rice and its fractions. *Korean J. Food Sci. Technol.* 45, 262–266. doi: 10.9721/KJFST.2013.45.2.262

Kwon, K. S., Hwang, W. S., Lee, K. H., Kim, K. J., Lee, W. Y., Kim, J., et al. (2023). Protection of allergic asthma in mice by black rice bran bioprocessed with shiitake mushroom mycelia. *Food Nutr. Sci.* 14, 341–368. doi: 10.4236/fns.2023.144023

Kwon, K. S., Lee, E. S., Lee, K. H., Hwang, W. S., Lee, W. Y., Kim, J. J., et al. (2024). Anti-obesity and other health benefits of bioprocessed black rice bran in combination with green tea extract in 3T3-L1 preadipocyte cells and in mice on a high-fat diet. *Food Funct.* 15, 12083–12100. doi: 10.1039/D4FO03210A

Lee, K. H., Kwon, K. S., Hwang, W. S., Lee, W. Y., Kim, J., Lee, S. J., et al. (2023). Bioprocessed black rice bran potentiates the growth inhibitory activity of an immune checkpoint inhibitor against murine colon carcinoma. *Food Nutr. Sci.* 14, 1149–1171. doi: 10.4236/fns.2023.1412072

Lee, J. H., Lee, M., Min, H., Youn, E., and Shim, Y.-H. (2022). Maternal gliadin intake reduces oocyte quality with chromosomal aberrations and increases embryonic lethality through oxidative stress in a *Caenorhabditis elegans* model. *Nutrients* 14:5403. doi: 10.3390/nu14245403

- Li, X., Zhang, Y., Wang, S., Shi, C., Wang, S., Wang, X., et al. (2022). A review on the potential use of natural products in overweight and obesity. *Phytother. Res.* 36, 1990–2015. doi: 10.1002/ptr.7426
- Limtrakul, P., Yodkeeree, S., Pitchakarn, P., and Punfa, W. (2015). Suppression of inflammatory responses by black rice extract in raw 264.7 macrophage cells via downregulation of Nf-kB and Ap-1 signaling pathways. *Asian Pac. J. Cancer Prev.* 16, 4277–4283. doi: 10.7314/APJCP.2015.16.10.4277
- Ling, W. H., Cheng, Q. X., Ma, J., and Wang, T. (2001). Red and black Rice decrease atherosclerotic plaque formation and increase antioxidant status in rabbits. *J. Nutr.* 131, 1421–1426. doi: 10.1093/jn/131.5.1421
- Liu, D., Ji, Y., Zhao, J., Wang, H., Guo, Y., and Wang, H. (2020). Black rice (*Oryza sativa* L.) reduces obesity and improves lipid metabolism in C57bl/6j mice fed a high-fat diet. *J. Funct. Foods* 64:103605. doi: 10.1016/j.jff.2019.103605
- Mckay, R. M., Mckay, J. P., Avery, L., and Graff, J. M. (2003). *C. elegans*: a model for exploring the genetics of fat storage. *Dev. Cell* 4, 131–142. doi: 10.1016/S1534-5807(02)00411-2
- O'rouke, E. J., Soukas, A. A., Carr, C. E., and Ruvkun, G. (2009). *C. elegans* major fats are stored in vesicles distinct from lysosome-related organelles. *Cell Metab.* 10, 430–435. doi: 10.1016/j.cmet.2009.10.002
- Papsdorf, K., Miklas, J. W., Hosseini, A., Cabruja, M., Morrow, C. S., Savini, M., et al. (2023). Lipid droplets and peroxisomes are co-regulated to drive lifespan extension in response to mono-unsaturated fatty acids. *Nat. Cell Biol.* 25, 672–684. doi: 10.1038/s41556-023-01136-6
- Saravanan, A., Karishma, S., Kumar, P. S., and Rangasamy, G. (2023). A review on regeneration of biowaste into bio-products and bioenergy: life cycle assessment and circular economy. *Fuel* 338:127221. doi: 10.1016/j.fuel.2022.127221
- Stiernagle, T. (2006). Maintenance of *C. elegans*. WormBook: the online review of *C. elegans* biology. doi: 10.1895/wormbook.1.101.1
- Tepwong, P., Giri, A., and Ohshima, T. (2012). Effect of mycelial morphology on ergothioneine production during liquid fermentation of *Lentinula edodes*. *Mycoscience* 53, 102–112. doi: 10.1007/S10267-011-0145-0
- Wang, F.-Y., and Ching, T.-T. (2021). Oil red O staining for lipid content in *Caenorhabditis elegans*. *Bio-protocol* 11:e4124–e4124. doi: 10.21769/BioProtoc.4124
- Zhang, H., Zhou, X.-D., Shapiro, M. D., Lip, G. Y., Tilg, H., Valenti, L., et al. (2024). Global burden of metabolic diseases, 1990–2021. *Metabolism* 160:155999. doi: 10.1016/j.metabol.2024.155999
- Zhao, X. Y., Wang, J. Q., Neely, G. G., Shi, Y. C., and Wang, Q. P. (2024). Natural compounds as obesity pharmacotherapies. *Phytother. Res.* 38, 797–838. doi: 10.1002/ptr.8083