Biological age in the meta omics era: integrating physical activity, sleep, and diet to reshape paths of healthy ageing

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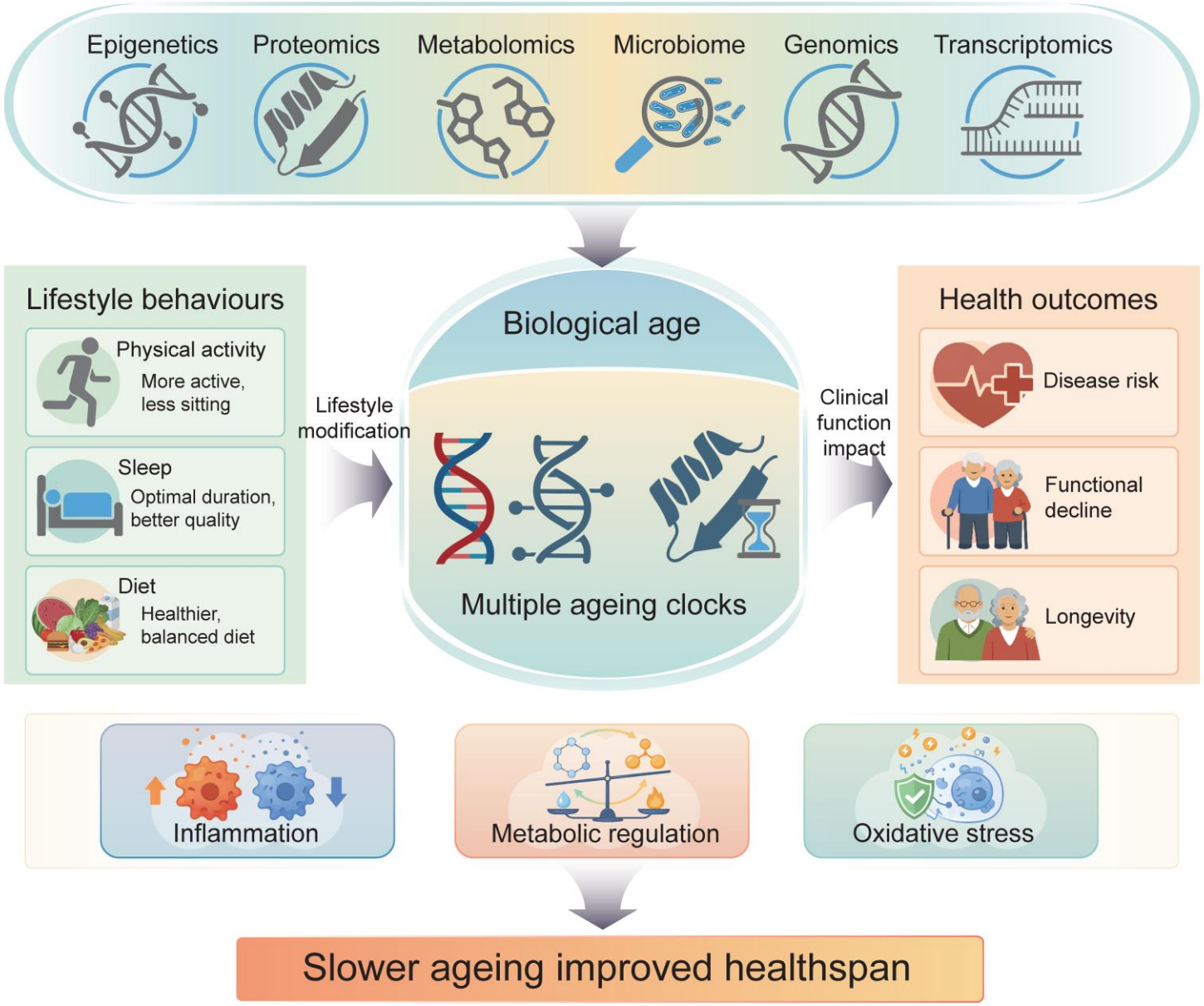
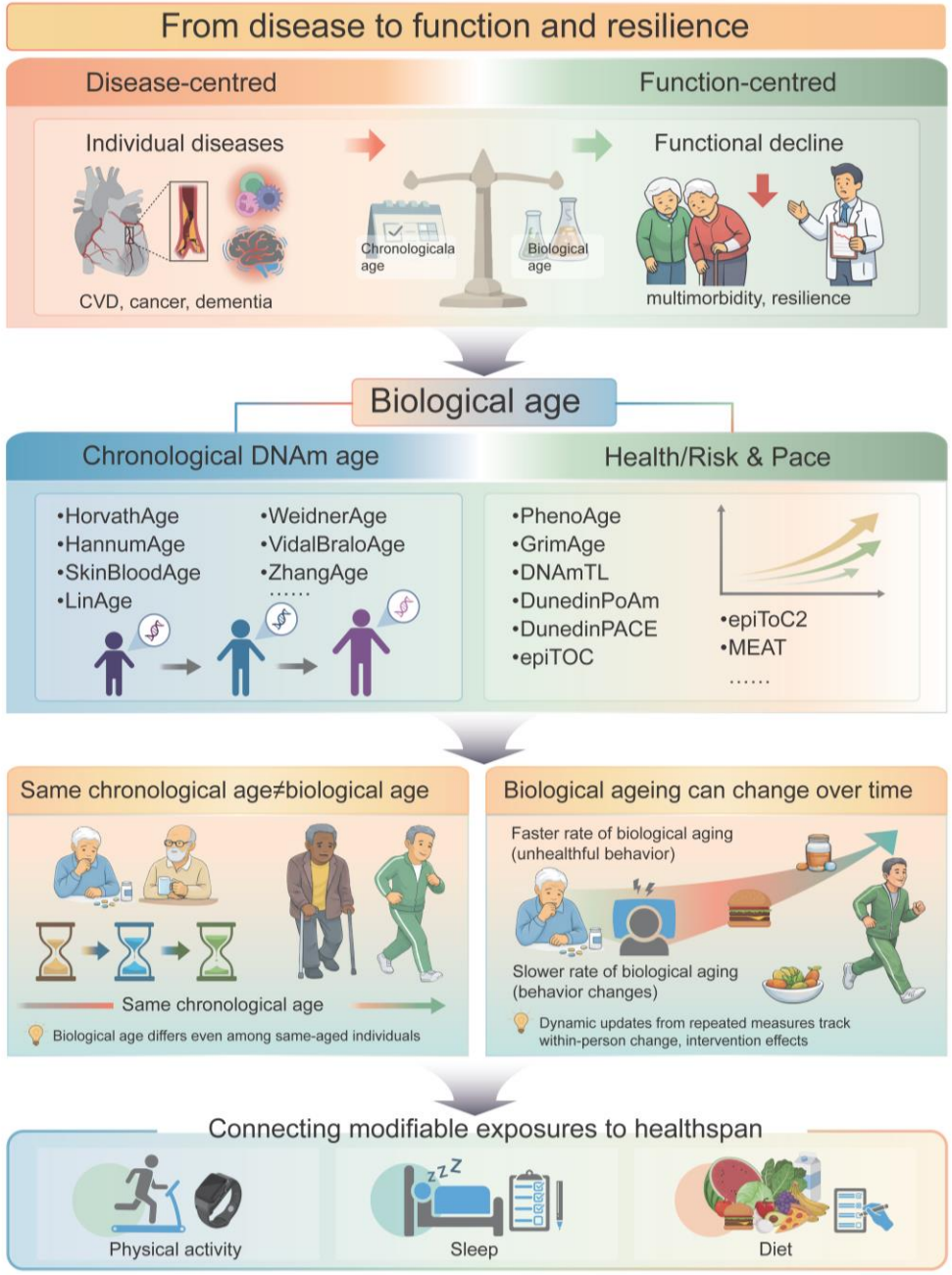
Highlights



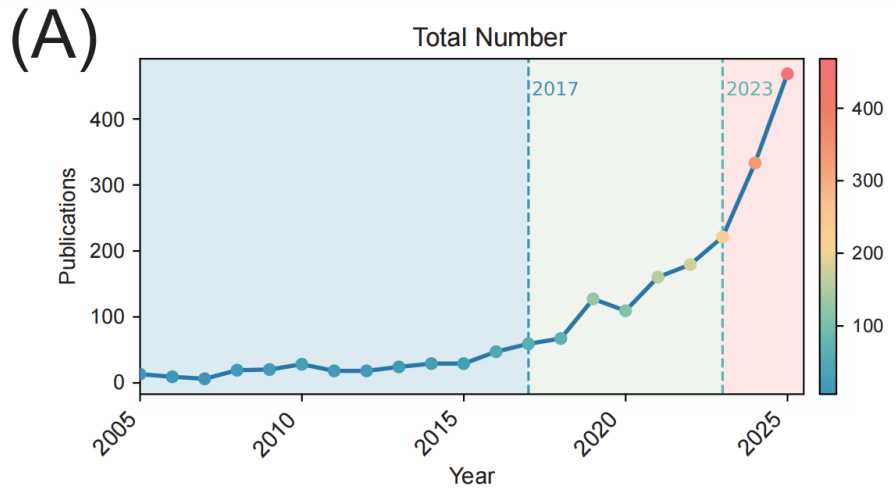
- Biological age provides a translational endpoint linking modifiable lifestyle behaviours—physical activity, sleep, and diet—to multi-omics changes and downstream clinical outcomes.
- Integrating multiple ageing clocks with inflammatory, metabolic and oxidative pathways supports reproducible, intervention-ready strategies to slow ageing and extend healthspan.

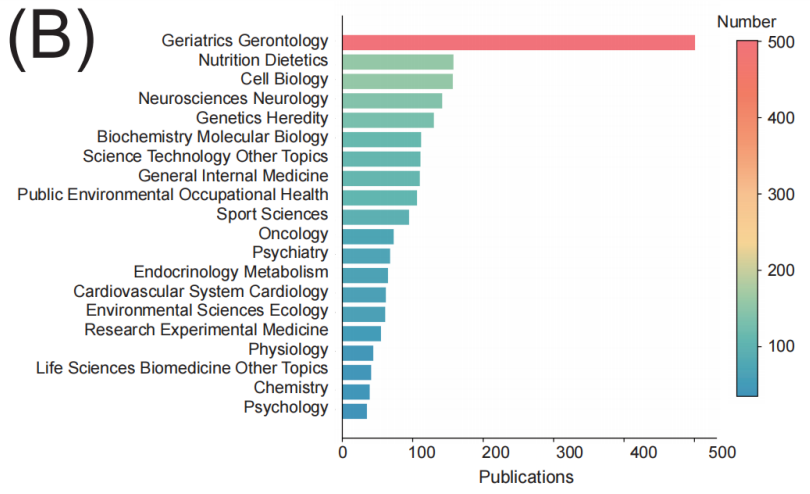
Integrate meta-omics, biological age, and lifestyle factors

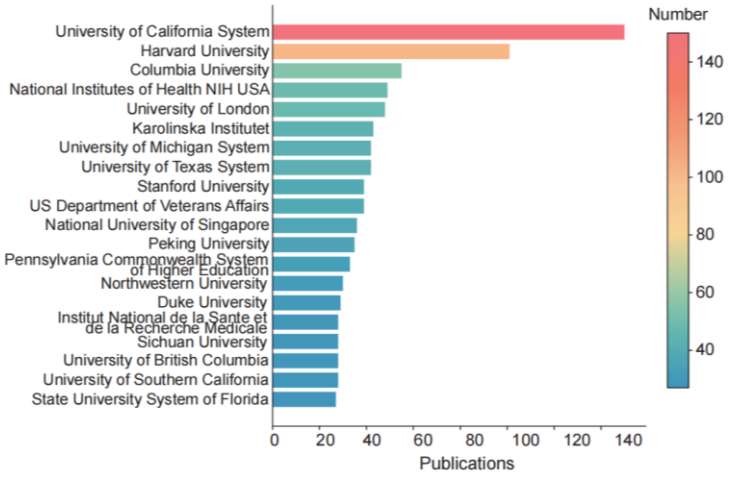


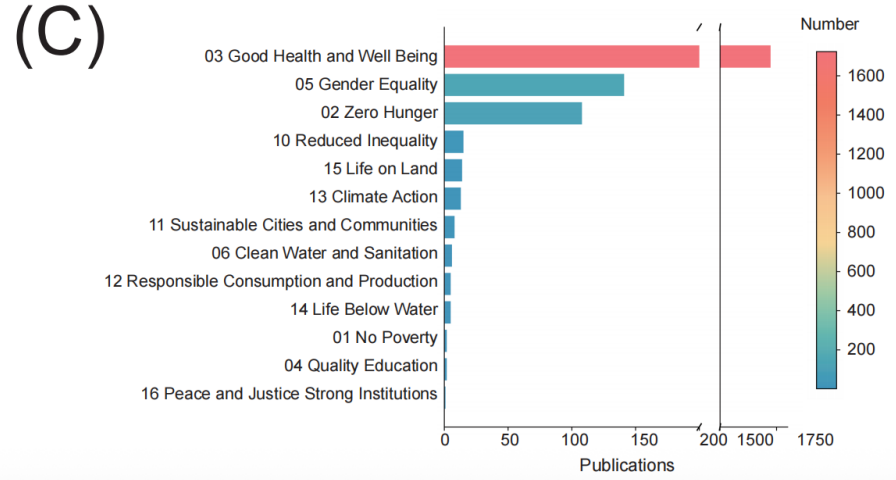
- It is essential to integrate meta-omics, biological age, and lifestyle factors. Figure 1 summarises the conceptual model: positioning biological age as a primary endpoint, or as a mediator linking lifestyle exposures to functional outcomes, offers several practical advantages for healthy ageing research.
- First, many biological age measures provide stronger prediction of downstream outcomes than chronological age alone, including disability, frailty-relevant phenotypes, multimorbidity, and all-cause mortality, which is central for translating observational evidence into clinically meaningful risk stratification.
- Second, biological age measures are more sensitive to cumulative environmental and behavioural influences, supporting analyses that quantify how physical activity, sleep patterns, and diet quality relate to multi-system ageing burden rather than isolated disease endpoints.
- Third, biological age is well-suited to repeated-measurement designs: within-person change over time can be modelled as a dynamic outcome, enabling stronger longitudinal inference about temporal ordering and responsiveness to intervention.

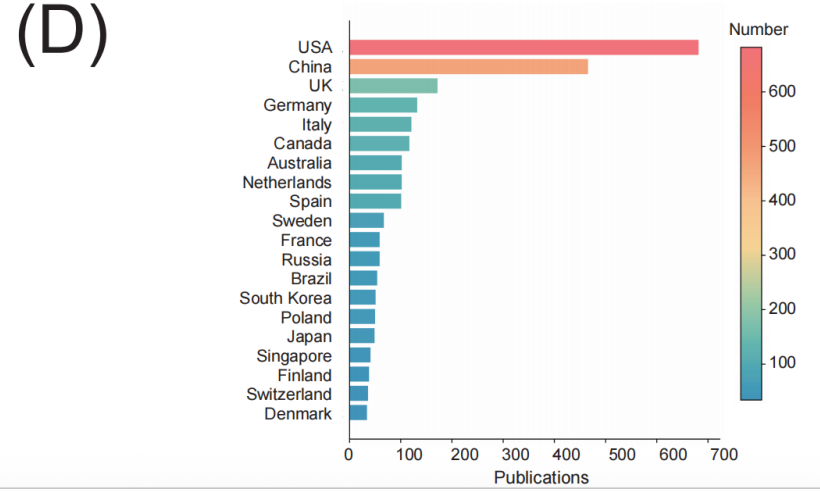
Bibliometric analysis and knowledge map





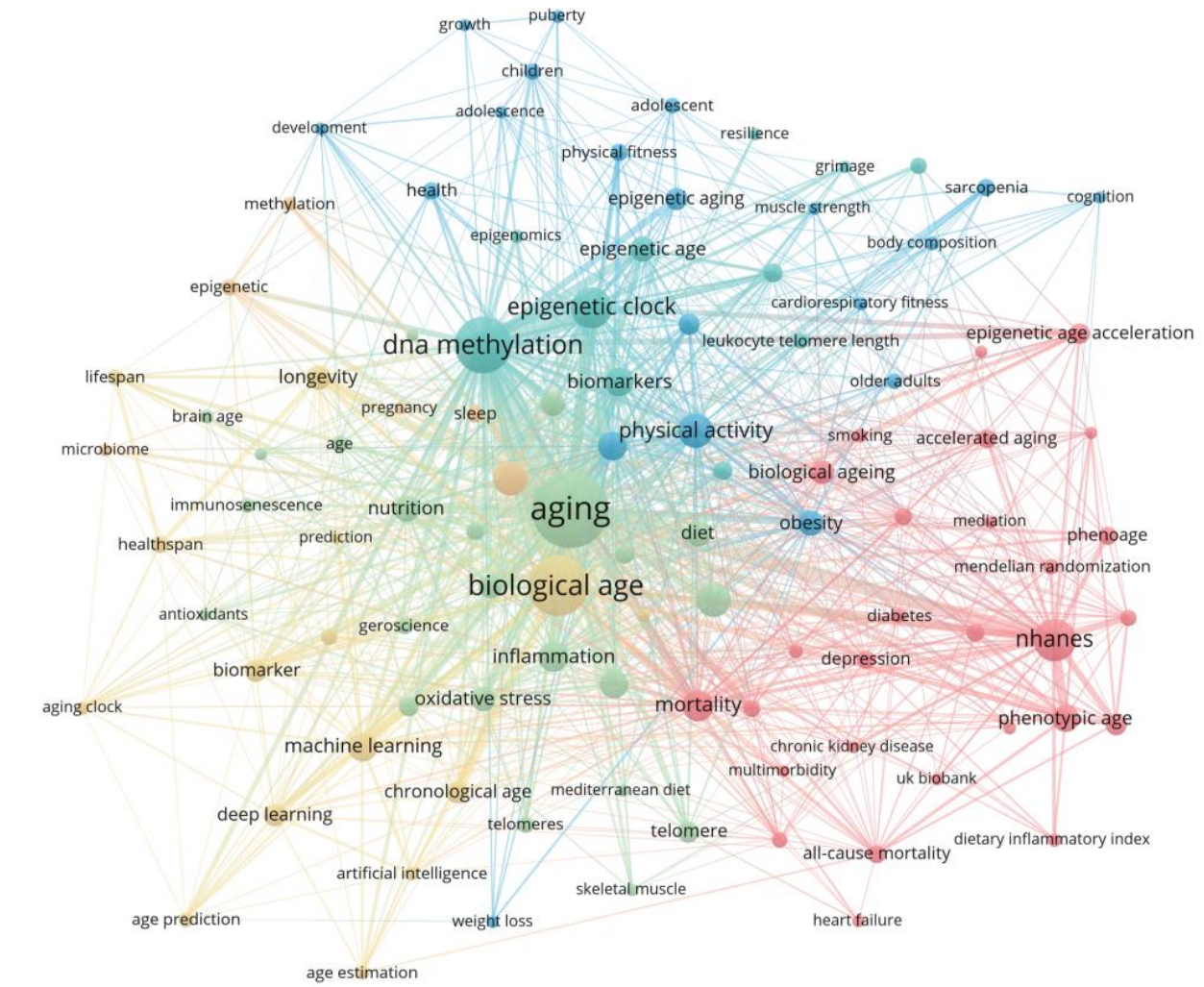


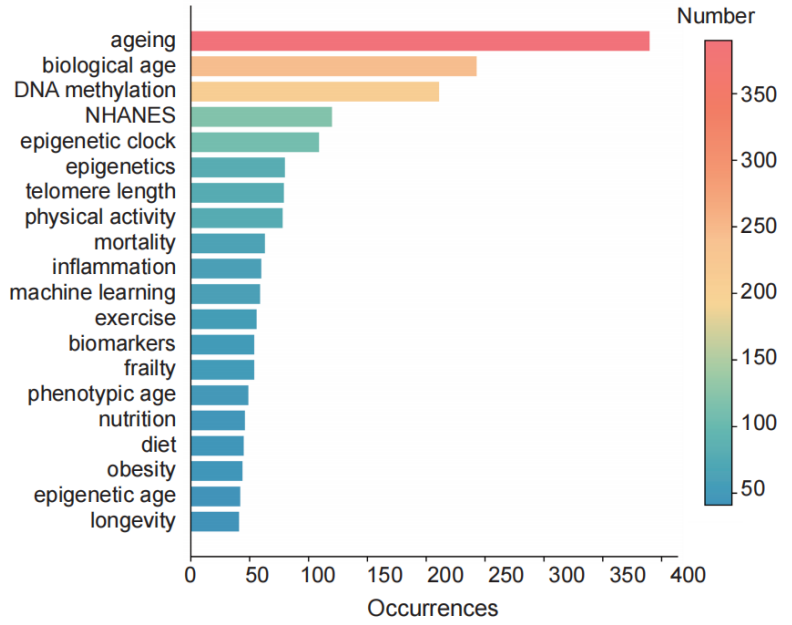


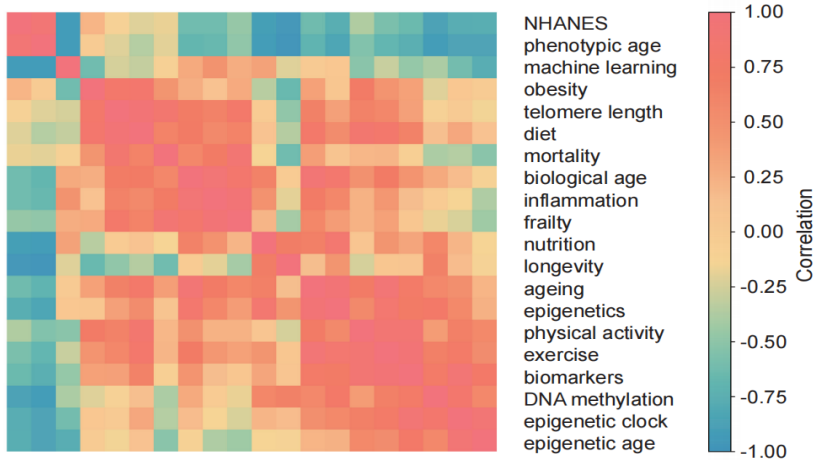


- Research on biological age and lifestyle increased markedly after 2017 and entered a second phase of expansion around 2023.
- Biological age has expanded from a methodological tool in molecular ageing research into a common endpoint linking behavioural exposures, systemic physiological dysregulation, and clinical outcomes.

Bibliometric analysis and knowledge map







- The keyword network showed that “ageing,” “biological age,” “epigenetic age,” “DNA methylation,” and “physical activity” formed a highly interconnected core, surrounded by themes including mortality, chronic disease, inflammation, biomarkers, telomere length, diet and nutrition, and machine learning.

Summary and future perspective

- Future research on precision healthy ageing should first establish a clear conceptual pathway: how lifestyle behaviours influence multi-omics profiles, how multi-omics features correspond to changes in biological age, and how changes in biological age are associated with functional performance, disease burden, and survival outcomes. Positioning biological age at the centre of this pathway may facilitate comparisons across cohorts, exposures, and ageing clocks.
- In terms of study design, priority should be given to longitudinal cohorts with repeated measurements. Simultaneously tracking temporal changes in physical activity, sleep, diet, and biological age is essential for distinguishing stable inter-individual differences from genuine within-person changes and for determining whether lifestyle changes precede changes in biological age. Wearable devices can provide more detailed behavioural phenotypes, including activity dose, intensity, rhythmicity, and sedentary patterns, thereby offering high-resolution exposure information for biological ageing research.
- Randomized trials and real-world interventions are equally important. Determining whether lifestyle modification can genuinely slow biological age acceleration requires observing changes in biological age indicators under controlled conditions or in real-world settings. At the same time, multi-omics data preprocessing, biological age calculation, quality control, batch correction, and external validation should become more transparent and standardized to improve comparability across studies.
- Methodologically, target trial emulation can help researchers define research questions, eligibility criteria, intervention strategies, follow-up windows, and outcomes more clearly when using observational data. Mendelian randomization may serve as a complementary approach for evaluating potential causal relationships involving selected exposures or intermediate pathways.

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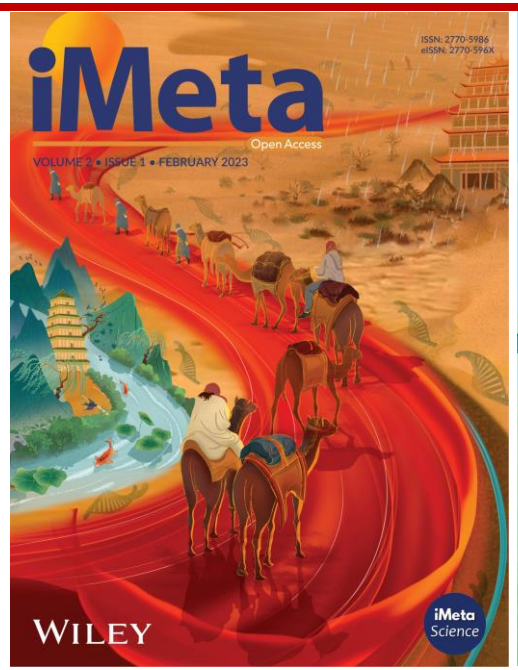

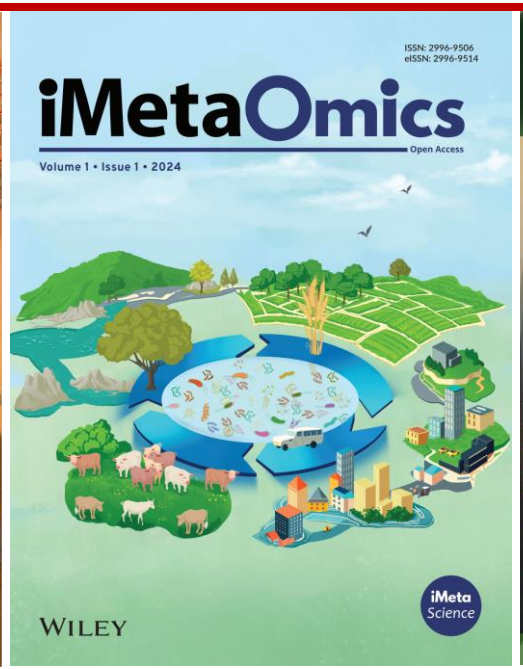

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