

Association between residential greenness and the risk of inflammatory bowel disease in patients with COVID-19: A Korean nationwide cohort study

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Abstract

Background: Residential greenness has been associated with reduced risk of inflammatory bowel disease (IBD), but its association in the context of COVID-19, a condition associated with increased IBD risk, remains unclear. We evaluated whether the protective association between greenness and IBD persisted among individuals with SARS-CoV-2 infection.

Methods: We conducted a nationwide cohort study of 6,900,341 individuals with confirmed COVID-19 in South Korea, using linked data from the National Health Insurance Service, Korea Disease Control and Prevention Agency, and satellite-derived normalized difference vegetation index (NDVI) from NASA's Terra MODIS (MOD13A3, version 6.1). Individuals were categorized into low (0.2 to <0.4), moderate (0.4 to <0.6), or high (≥ 0.6) NDVI groups. The primary outcome was incident IBD (Crohn's disease and ulcerative colitis) ≥ 30 days after infection, defined using ICD-10 codes. Inverse probability of treatment weighting balanced covariates, and weighted Cox models estimated adjusted hazard ratios (aHRs) with 95% confidence intervals (CIs).

Results: Higher residential greenness was associated with lower risk of developing IBD following COVID-19 infection, with aHRs of 0.93 (95% CI, 0.90–0.97) for moderate and 0.71 (0.68–0.74) for high NDVI compared with low. Subtype analyses showed more consistent associations for ulcerative colitis (aHR 0.91 [95% CI,

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0.87–0.96] for moderate; aHR 0.60 [0.57–0.63] for high NDVI). For Crohn's disease, associations were weaker and limited to individuals exposed to high NDVI (aHR, 0.90 [95% CI, 0.85–0.96]). Associations were more apparent among individuals with mild COVID-19 and were stronger among females, adults aged 40 to 59 years, and those with pre-existing comorbidities.

Conclusions: Higher residential greenness was associated with a lower incidence of IBD after COVID-19. Maintaining access to greenness during periods of restricted mobility may help counteract infection-related inflammation.

Keywords: COVID-19, inflammatory bowel disease, normalized difference vegetation index

INTRODUCTION

The gut microbiota-immune-brain axis is increasingly recognized as a central pathway in the pathogenesis of inflammatory bowel disease (IBD), including Crohn's disease and ulcerative colitis, characterized by chronic intestinal inflammation.^[1] Exposure to natural environments has been associated with modulation of this axis, with residential greenness associated with greater microbial diversity, reduced immune activation, and enhanced immune tolerance.^[2,3] Consistent with these mechanisms, several observational studies have reported lower incidences of IBD among individuals living in greener areas, potentially through reductions in systemic inflammation and improvements in gut microbiome composition.^[2,4]

Meanwhile, COVID-19 has been associated with increased IBD risk as a possible postinfectious complication.^[5,6] This association is biologically plausible, given that SARS-CoV-2 infection provokes immune dysregulation through excess inflammatory cytokine release and increased T-helper 17 activity, pathways that are central to IBD pathogenesis.^[7] We therefore hypothesized that while COVID-19 may increase susceptibility to IBD, exposure to residential greenness could counteract this risk through anti-inflammatory and microbiome-supporting mechanisms. However, the extent to which residential greenness influences IBD risk in the context of COVID-19 remains poorly understood.^[2]

To address this gap, we conducted a nationwide, population-based cohort study in South Korea using linked administrative and clinical data from the National Health Insurance Service (NHIS) of Korea, COVID-19-related data from the Korea Disease Control and Prevention Agency (KDCA), and satellite-derived greenness data based on residential GPS coordinates. We evaluated whether residential greenness, measured using the normalized difference vegetation index (NDVI), was associated with incident IBD following COVID-19, including subtype analyses for ulcerative colitis and Crohn's disease, and

stratified analyses by age, sex, comorbidity status, physical activity, and income level.

PATIENTS AND METHODS

Data source

In this study, South Korea's universal single-payer healthcare system provided comprehensive population coverage, allowing longitudinal follow-up across all levels of care, including outside hospital care. Within this system, the K-COV-N cohort was developed by linking health examination and healthcare utilization data from the NHIS of Korea with COVID-19 records from the KDCA.^[8] The dataset covered the period from January 1, 2018, to December 31, 2023.^[8] Residential greenness exposure was assessed using the NDVI, derived from National Aeronautics and Space Administration's Terra satellite Moderate Resolution Imaging Spectroradiometer product MOD13A3 (version 6.1), and linked to participants' home GPS coordinates.^[9]

Study population

Eligible participants included individuals aged 19 years or older with laboratory-confirmed SARS-CoV-2 infection [Figure 1(a)]. Infection confirmation utilized real-time RT-PCR assays of nasal or throat swab samples, conducted according to KDCA-approved methods following WHO recommendations. Within the COVID-19 study cohort, positive RT-PCR results determined infection status.^[10] To minimize bias from residential mobility, only individuals with consistent address records during both the year prior to infection and the year of COVID-19 diagnosis were included. The reference date was defined as the date of confirmed infection, and follow-up continued until the earliest of the following: death, first occurrence of the outcome of interest, or December 31, 2023. Participants with prior diagnoses of the outcome before the reference date, or with incomplete covariate information, were excluded. Pre-existing medical conditions were identified using records from January 1, 2018 up to the index date,

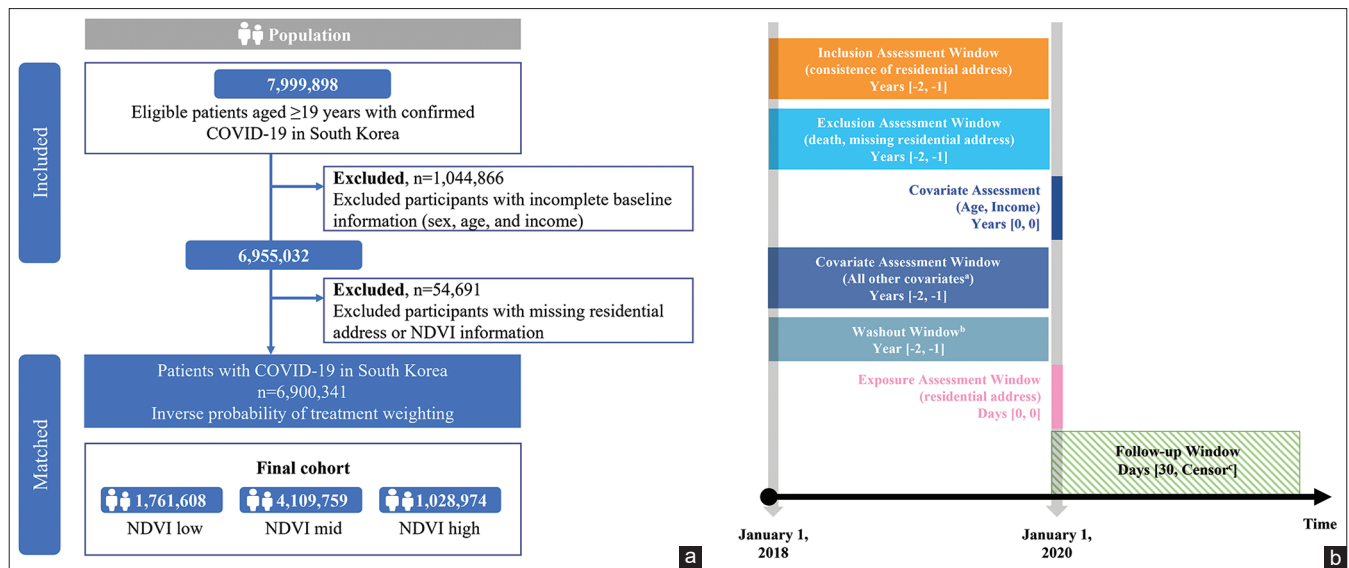


Figure 1: (a) Flow chart and (b) study diagram. ^aAll-other covariates: Charlson comorbidity index, Body mass index, blood pressure, fasting blood glucose, glomerular filtration rate, smoking status, alcohol consumption, and aerobic physical activity. ^bWashout period applied to identify newly diagnosed cases between 2020 and 2023 by excluding individuals with relevant medical records from 2018 to 2019. ^cParticipants were censored at the earliest occurrence of death, first diagnosis of the outcome, or at the end of the study period (December 31, 2023)

and follow-up was conducted from January 1, 2020 through December 31, 2023 [Figure 1(b)]. All analyses used de-identified administrative data, for which informed consent was not required by regulation.

Exposure

Greenspace exposure was evaluated using the NDVI, a satellite-derived metric calculated from near-infrared and visible light reflectance as their difference divided by their sum, representing photosynthetically active vegetation.^[11] Data were obtained from the Terra satellite's Moderate Resolution Imaging Spectroradiometer (MOD13A3, version 6.1), which provided monthly estimates at a spatial resolution of 1 km, from January 2018 through December 2023. For each of South Korea's 282 Si-Gun-Gu districts, mean NDVI values were linked to participants' residential areas. To address potential exposure misclassification due to residential mobility, we restricted the study population to individuals with consistent residential address records during the year preceding and the year of COVID-19 diagnosis, ensuring that assigned district-level NDVI reflected stable residential location over the relevant exposure window. Exposure categories were defined as low (0.2 to <0.4 , reference), moderate (0.4 to <0.6), and high (≥ 0.6), consistent with previous studies.^[12,13] The geographical distribution of NDVI measurements throughout South Korea is illustrated in Supplementary Figure 1.

Outcome

The primary outcome was defined as the first recorded diagnosis of IBD, identified using the International

Classification of Diseases, 10th Revision (ICD-10). IBD cases were classified as Crohn's disease (K50) or ulcerative colitis (K51). To reduce the possibility of reverse causation, only diagnoses recorded at least 30 days after laboratory-confirmed SARS-CoV-2 infection were included.^[8]

Covariates

We adjusted for a wide range of demographic, clinical, and behavioral factors to address potential confounding. Demographic information was obtained from the national health insurance database, including sex, age group (categorized as 19–39, 40–59, and ≥ 60 years), and household income level divided into tertiles (low [0–39th percentile], middle [40–79th percentile], and high [80–100th percentile]). Clinical measurements were obtained from standardized national health screening records. Blood pressure was classified as normal (systolic <140 mmHg and diastolic <90 mmHg) or elevated (systolic ≥ 140 mmHg and/or diastolic ≥ 90 mmHg). Estimated glomerular filtration rate (eGFR) was categorized as <60 or ≥ 60 mL/min/1.73 m². Body mass index (BMI) was categorized according to Asia-Pacific regional criteria: underweight (<18.5 kg/m²), normal weight (18.5–22.9 kg/m²), overweight (23.0–24.9 kg/m²), and obese (≥ 25.0 kg/m²).^[14,15] Fasting blood glucose levels were divided into <100 or ≥ 100 mg/dL.^[8,14,15] All laboratory results were obtained from fasting samples collected at health check-ups. Additional health status indicators included the Charlson comorbidity index (CCI), mental disorders, antihypertensive medications use, and treatment

history for diabetes mellitus and dyslipidemia.^[8] Mental disorders were defined using ICD-10 codes for psychotic disorders (F20–F29), mood disorders (F30–F39), anxiety and stress-related disorders (F40–F48), and nonorganic sleep disorders including nonorganic insomnia (F51). Lifestyle-related variables included smoking status (never, former/current smoker, or unknown), weekly alcohol consumption frequency (<1 day, 1–2 days, 3–4 days, ≥5 days, and unknown), and aerobic physical activity level. Sufficient physical activity was defined as ≥600 metabolic equivalent minutes per week, in accordance with World Health Organization guidelines.^[16] Missing values for all covariates were addressed using the missing indicator methodology. Based on the literature and expert knowledge,^[2] we illustrated the hypothesized causal relationship using a directed acyclic graph representing the effect of all covariates in relation to NDVI and the mental health outcomes [Figure S2].

Inverse probability of treatment weighting

We used inverse probability of treatment weighting (IPTW) to enhance comparability among the NDVI exposure groups. The weighting model incorporated age, sex, household income, medication history, CCI, BMI, blood pressure, fasting glucose, eGFR, smoking status, alcohol intake, and level of aerobic physical activity. After weighting, covariate balance was evaluated using standardized mean differences (SMDs), with values below 0.1 considered indicative of adequate balance between exposure groups [Figure S3]. Baseline characteristics of the cohort prior to weighting are presented in Table S1, while IPTW-adjusted distributions across NDVI categories are reported in Table 1.

Statistical analysis

IPTW based on propensity scores was first applied to address imbalance in baseline characteristics across NDVI exposure groups.^[8] The propensity score model included age, sex, household income, BMI, BP, FBG, eGFR, CCI, mental disorders, medication history, smoking status, alcohol consumption, and physical activity. After weighting, Cox proportional hazards regression models were used to estimate adjusted hazard ratios (aHRs) with 95% confidence intervals (CIs). The same set of covariates used in the propensity score model was also included in the regression analyses. The proportional hazards assumption was evaluated using tests based on scaled Schoenfeld residuals, and no meaningful violations were identified. The index date was defined as the date of SARS-CoV-2 diagnosis. In the primary analysis, follow-up began 30 days after the index date to reduce the possibility of reverse causation and detection bias, and continued

until the earliest of outcome occurrence, death, or Dec 31, 2023. To examine the robustness of our findings to alternative latency definitions, we conducted sensitivity analyses extending the latency window to 90 days and 180 days after diagnosis [Table S2]. Statistical significance was defined as a two-sided *P* value below 0.05. All analyses were conducted using SAS software, version 9.4 (SAS Institute, Cary, NC, USA).

Ethical statement

Ethical approval was obtained from the Institutional Review Board of Kyung Hee University (KHSIRB-23-241[EA]), with authorization granted by the KDCA and NHIS (KDCA-NHIS-2025-04-1-105). All analyses used de-identified administrative data, for which informed consent was not required by regulation.

RESULTS

Study population

From eight million individuals aged 19 years or older with confirmed COVID-19 in South Korea, we assessed eligibility for inclusion. We excluded 1,099,557 individuals who had incomplete baseline information, missing residential address information, died before the index date, or had inconsistent address records in the year prior to infection. The remaining 6,900,341 individuals were categorized into low, moderate, and high residential NDVI groups. To improve comparability across exposure categories, we applied IPTW based on propensity scores. After weighting, the effective sample sizes were approximately 1,761,608 in the low-NDVI group, 4,109,759 in the moderate-NDVI group, and 1,028,974 in the high-NDVI group [Table 1].

Normalized difference vegetation index exposure and risk of inflammatory bowel disease

Residential greenness was associated with a lower risk of IBD. Compared with low NDVI, both moderate NDVI (aHR, 0.93 [95% CI, 0.90 to 0.97]) and high NDVI (0.71 [0.68 to 0.74]) exposures were associated with lower IBD risk [Figure 2]. In subtype-specific analyses, associations were stronger and more consistent for ulcerative colitis. Moderate NDVI (aHR, 0.91 [95% CI, 0.87 to 0.96]) and high NDVI (0.60 [0.57 to 0.63]) exposures were both associated with lower risk of ulcerative colitis. For Crohn's disease, moderate NDVI was not associated with disease risk (aHR, 0.96 [95% CI, 0.90 to 1.03]). However, high NDVI was associated with a modestly lower risk (aHR, 0.90 [95% CI, 0.85 to 0.96]) [Figure 2]. Schoenfeld residual tests were broadly consistent with the proportional hazard's assumption across outcomes (IBD, *P* = 0.623; UC, *P* = 0.071; CD, *P* = 0.378).

Table 1. 1:1:1 IPTW propensity score weighted characteristics of cohort (n=6,900,341)

Baseline characteristic	Total	T1 ^a	T2 ^a	T3 ^a
Total	6,900,341	1,761,608	4,109,759	1,028,974
Age (y), mean±SD	47.34±13.81	47.36±27.33	47.34±17.84	47.30±36.51
Sex, n (%)				
Men	3,915,499 (56.74)	(56.83)	(56.74)	(56.74)
Women	2,984,842 (43.26)	(43.17)	(43.26)	(43.26)
Baseline income, n (%)				
Q1	2,062,945 (29.90)	(30.48)	(29.84)	(29.70)
Q2	2,937,168 (42.57)	(41.63)	(42.69)	(43.61)
Q3	1,900,228 (27.54)	(27.89)	(27.47)	(26.69)
BMI, n (%)				
Underweight	219,619 (3.18)	(3.21)	(3.17)	(3.17)
Normal	2,300,387 (33.34)	(33.23)	(33.36)	(33.29)
Overweight	1,579,992 (22.90)	(22.88)	(22.90)	(22.93)
Obesity	2,800,343 (40.58)	(40.68)	(40.58)	(40.61)
Charlson comorbidity index, n (%)				
0	6,261,985 (90.75)	(90.96)	(90.74)	(90.39)
1	356,900 (5.17)	(4.68)	(5.18)	(5.81)
≥2	281,456 (4.08)	(4.36)	(4.07)	(3.79)
Blood pressure, n (%)				
SBP<140 and DBP<90	6,026,650 (87.34)	(87.33)	(87.34)	(87.42)
SBP≥140 or DBP≥90	873,691 (12.66)	(12.67)	(12.66)	(12.58)
Fasting blood sugar, n (%)				
<100 mg/dL	4,328,593 (62.73)	(62.66)	(62.73)	(62.74)
≥100 mg/dL	2,571,748 (37.27)	(37.34)	(37.27)	(37.26)
Glomerular filtration rate, n (%)				
<60 mL/min/1.73 m ²	168,011 (2.43)	(2.42)	(2.41)	(2.56)
≥60 mL/min/1.73 m ²	6,732,330 (97.57)	(97.58)	(97.59)	(97.44)
Smoking status, n (%)				
Never	6,833,086 (99.03)	(98.95)	(99.04)	(99.12)
Former/Current	64,198 (0.93)	(1.00)	(0.92)	(0.84)
Unknown	3057 (0.04)	(0.04)	(0.04)	(0.04)
Alcohol consumption, n (%)				
<1 day/week	4,153,973 (60.20)	(59.08)	(60.48)	(61.07)
1–2 days/week	1,920,773 (27.84)	(28.64)	(27.71)	(26.97)
3–4 days/week	638,739 (9.26)	(9.54)	(9.14)	(9.18)
≥5 days/week	183,731 (2.66)	(2.69)	(2.62)	(2.74)
Unknown	3125 (0.05)	(0.04)	(0.05)	(0.04)
Physical activity, n (%)				
Insufficient	3,252,517 (47.14)	(47.37)	(47.42)	(45.28)
Sufficient	3,644,640 (52.82)	(52.58)	(52.53)	(54.67)
Unknown	3184 (0.05)	(0.05)	(0.05)	(0.05)
Mental disorders, n (%)				
No	5,594,313 (81.07)	(81.12)	(81.07)	(81.15)
Yes	1,306,028 (18.93)	(18.88)	(18.93)	(18.85)
Medication for hypertension, n (%)				
No	5,787,030 (83.87)	(83.81)	(83.87)	(83.85)
Yes	1,113,311 (16.13)	(16.19)	(16.13)	(16.15)
Medication for diabetes mellites, n (%)				
No	6,420,334 (93.04)	(93.03)	(93.04)	(93.04)
Yes	480,007 (6.96)	(6.97)	(6.96)	(6.96)
Medication for dyslipidemia, n (%)				
No	6,329,681 (91.73)	(91.71)	(91.73)	(91.74)
Yes	570,660 (8.27)	(8.29)	(8.27)	(8.26)

BMI, body mass index; IPTW, inverse probability of treatment weighting; NDVI, normalized difference vegetation index; SD, standard deviation. ^a T1, low NDVI group; T2, medium NDVI group; T3, high NDVI group

Stratification analysis by COVID-19 severity and SARS-CoV-2 variant

Inverse associations between residential greenness and incident IBD differed by COVID-19 severity. Among individuals with mild COVID-19, both moderate and high NDVI exposures were associated with lower IBD risk (moderate NDVI: aHR, 0.93 [95% CI, 0.90 to 0.97];

high NDVI: 0.71 [0.68 to 0.74]). Similar patterns were observed for ulcerative colitis (moderate NDVI: aHR, 0.91 [95% CI, 0.87 to 0.96]; high NDVI: 0.60 [0.57 to 0.64]), whereas associations for Crohn's disease were weaker and limited to high NDVI exposure (0.90 [0.85 to 0.96]). Among individuals with moderate-to-severe COVID-19, associations between NDVI and incident IBD were not

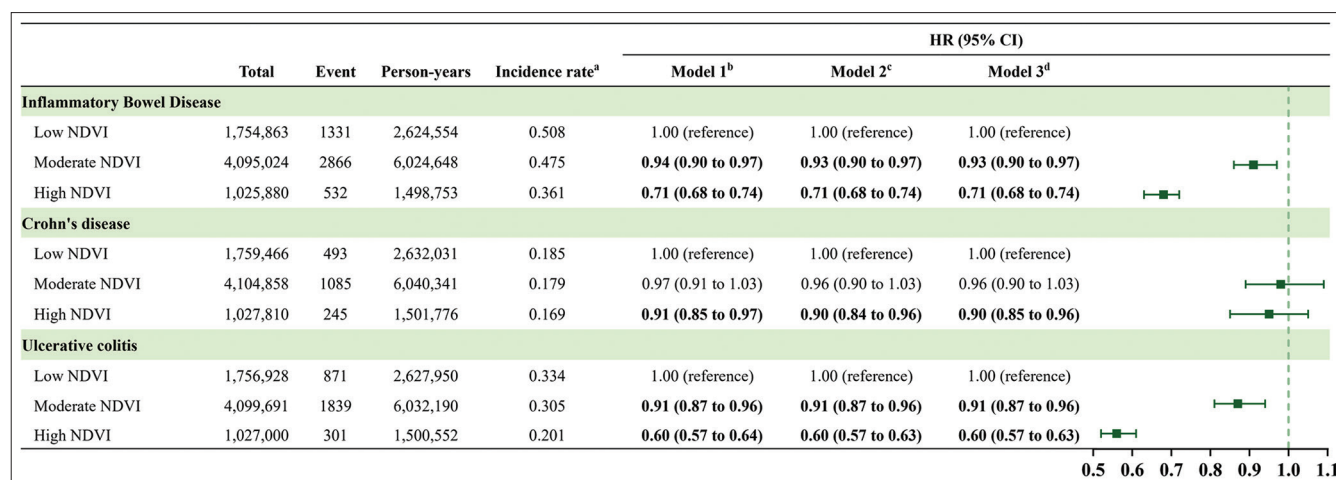


Figure 2: Hazard ratios for inflammatory bowel disease, Crohn's disease, and ulcerative colitis by NDVI exposure. Abbreviations: CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, body mass index, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, and weekly alcohol consumption frequency. ^dModel 3: adjusted for age, sex, household income, body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (P value < 0.05)

consistently observed and were accompanied by wider uncertainty [Table S3].

Associations between residential greenness and IBD also varied across SARS-CoV-2 variant periods. During the Omicron-dominant period, higher NDVI was associated with lower risk of overall IBD (moderate NDVI: aHR, 0.93 [95% CI, 0.89 to 0.96]; high NDVI: 0.70 [0.67 to 0.73]). Corresponding associations were observed for ulcerative colitis (moderate NDVI: aHR, 0.91 [95% CI, 0.87 to 0.96]; high NDVI: 0.60 [0.56 to 0.63]). For Crohn's disease, a modest association was observed only for high NDVI exposure (aHR, 0.89 [95% CI, 0.84 to 0.96]). However, during the original and delta strain period, associations between NDVI and IBD outcomes were not consistently observed [Table S4].

Stratification analysis across demographic and clinical subgroups

In sex-stratified analyses, reduced IBD risk was observed in both males and females, with greater risk reductions for high versus moderate NDVI exposure, and a stronger protective effect in females. Among males, the hazard ratio was 0.94 (95% CI, 0.89 to 0.99) for moderate NDVI and 0.69 (0.65 to 0.73) for high NDVI. Among females, corresponding estimates were 0.92 (95% CI, 0.86 to 0.98) and 0.73 (0.68 to 0.79). Similar sex-specific patterns were observed for ulcerative colitis. For Crohn's disease, however, risk reduction was observed only in males exposed to high NDVI (aHR, 0.90 [95% CI, 0.83 to 0.98]) [Figure 3 and Table S5].

In age-stratified analyses, high NDVI exposure was consistently associated with lower IBD risk across all age groups: aHR, 0.83 (95% CI, 0.78 to 0.89) for ages 19 to 39; 0.58 (0.54 to 0.62) for ages 40 to 59; and 0.76 (0.69 to 0.82) for ages ≥ 60 . For moderate NDVI, risk reduction was observed only in the 40 to 59 age group (aHR, 0.89 [95% CI, 0.84 to 0.95]), with no significant associations in younger or older individuals. Subtype analyses showed consistent risk reductions for ulcerative colitis across all age groups with high NDVI exposure. For Crohn's disease, reductions were limited to individuals aged 40 to 59 with high NDVI exposure (aHR, 0.70 [95% CI, 0.63 to 0.79]) [Figure 3 and Table S6].

In analyses stratified by comorbidity status, high NDVI exposure was associated with a lower risk of IBD both among individuals without comorbidities (aHR, 0.71 [95% CI, 0.68 to 0.74]) and among those with comorbidities (0.68 [0.60 to 0.76]). For Crohn's disease, high NDVI exposure was associated with a modest reduction in risk among individuals without comorbidities (aHR, 0.92 [95% CI, 0.86 to 0.98]) as well as among those with comorbidities (0.81 [0.67 to 0.99]). For ulcerative colitis, risk reductions were consistent across both groups, with the strongest association in individuals with comorbidities exposed to high NDVI (aHR, 0.59 [95% CI, 0.51 to 0.69]) [Figure 3 and Table S7].

Protective associations were observed across both insufficient and sufficient physical activity levels, and across all household income groups [Figure 3 and Table S8-9]. Similar patterns were also observed when analyses were

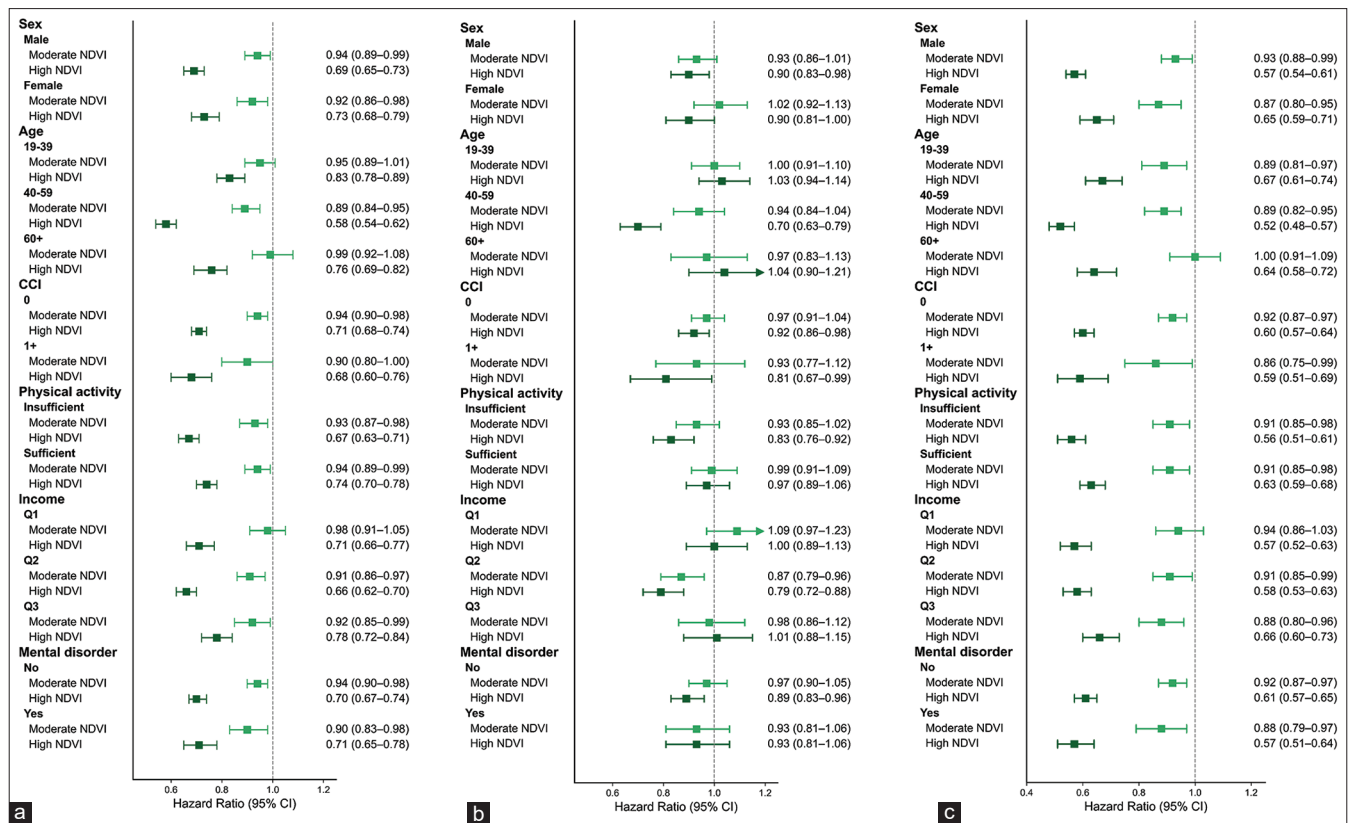


Figure 3: Hazard ratios for (a) inflammatory bowel disease, (b) Crohn's disease, and (c) ulcerative colitis by NDVI exposure and covariates. Abbreviations: CCI, Charlson comorbidity index; CI, confidence interval; NDVI, normalized difference vegetation index

stratified by mental health status, with inverse associations between high NDVI exposure and IBD risk present among individuals with and without mental disorders [Figure 3 and Table S10].

DISCUSSION

Key findings

In this nationwide cohort study of 6,900,341 individuals with COVID-19 in South Korea, we evaluated the association between residential greenness, as measured by NDVI, and the subsequent risk of IBD. First, higher residential greenness was associated with a lower incidence of IBD, with lower risks observed in high- and moderate-NDVI groups compared with low-NDVI groups. Second, subtype-specific analyses showed that associations were stronger and more consistent for ulcerative colitis, whereas for Crohn's disease a weaker association was observed only in the high-NDVI category. Third, in analyses stratified by COVID-19 severity, associations were more apparent among individuals with mild COVID-19. Fourth, in sex- and age-stratified analyses, inverse associations were more pronounced among females and among individuals aged 40 to 59 years. Fifth, inverse associations were stronger among individuals with pre-existing comorbidities. Finally,

associations between residential greenness and IBD were observed across income levels, physical activity strata, and mental health status, indicating that the observed patterns were not restricted to specific socioeconomic or lifestyle groups.

Comparisons with previous studies

Previous epidemiologic studies have consistently reported that higher residential greenness is associated with a lower risk of IBD, often suggesting a linear dose-response relationship.^[2,17,18] Most prior studies, however, have focused on childhood exposures and pediatric-onset disease.^[3] In contrast, our study evaluated adult-onset IBD and conducted age-stratified analyses, including <40, 40–59, and >60 years, to evaluate variation across the life course. A large United Kingdom cohort study of 216,868 participants aged 40–69 years similarly reported protective associations between residential greenness and IBD.^[4] However, greenness was measured using land-use classifications that quantify designated green space within residential buffers, which is an informative metric of accessibility, but may not adequately represent vegetation density or quality.^[4] By comparison, our use of the satellite-derived NDVI, a continuously updated measure of photosynthetically active vegetation, provides a more direct

indicator of biologically meaningful exposure.^[19] Our study also applied IPTW to balance covariates across exposure groups, thereby reducing confounding.^[20] Importantly, no previous studies have assessed this association during the COVID-19 pandemic, despite evidence that the pandemic may have influenced the incidence of IBD.

Plausible underlying mechanisms

Our findings suggest that residential greenness may reduce the risk of IBD following COVID-19 infection. Several biological pathways may help explain this association. The development of IBD involves an interplay between genetic susceptibility, mucosal immune responses, and gut microbial imbalance.^[21] Although the gut microbiota is generally stable, external factors such as infections can disrupt barrier function and dysregulate immunity, thereby contributing to disease onset.^[22] SARS-CoV-2 infection has been proposed as one such trigger, through viral tissue injury and cytokine-driven immune activation, with several case reports describing de novo onset of both Crohn's disease and ulcerative colitis after infection.^[7,23-25] However, our findings suggest that exposure to residential greenness may help counteract such disruptions. Higher levels of greenness have been associated with greater gut microbial diversity and increased abundance of beneficial genera such as *Lactobacillus* and *Bifidobacterium*, which strengthen epithelial barrier function and regulate intestinal inflammation.^[26,27] Greenness has also been associated with higher physical activity and reduced psychological stress, both of which influence immune balance and gut microbial composition through the gut-immune-brain axis.^[28] In addition, vegetated environments are related to lower exposure to air pollutants, which have been associated with intestinal barrier dysfunction and increased IBD risk.^[29]

The inverse association between residential greenness and ulcerative colitis, with weaker and less consistent associations observed for Crohn's disease, is consistent with findings from previous studies.^[17,30] One explanation is that Crohn's disease often develops more gradually and is more strongly affected by genetic susceptibility, which may have reduced the responsiveness to environmental conditions.^[2] In contrast, ulcerative colitis has been linked to postinfectious mucosal immune dysregulation and appears more responsive to environmental conditions.^[31] Crohn's disease is also frequently associated with delayed diagnosis and a prolonged subclinical phase, which may attenuate detectable associations in claims-based analyses.^[32] The lower incidence of Crohn's disease in Korea, and the correspondingly smaller number of cases in this study, may have further limited statistical power to detect an association.^[33] Accordingly, the proposed

biological mechanisms remain plausible, but cannot be directly evaluated, and the findings should be interpreted as associations rather than evidence of causality.

Strengths and limitations

Using a nationwide cohort of 6,900,341 individuals with confirmed COVID-19 in South Korea, we assessed the association between residential greenness and subsequent IBD with linked administrative records and satellite-based NDVI data. However, several limitations should be noted. First, residential greenness was measured using NDVI, which quantifies vegetation density in larger public spaces, but does not include smaller-scale or private green spaces.^[34] This may have resulted in non-differential exposure misclassification and attenuation of associations, and the findings should be interpreted in relation to ambient greenness exposure rather than individual access to or use of green spaces. Second, NDVI exposure was assigned according to residential address.^[35] Although this approach may not apply to all individuals, we restricted the study population to individuals with consistent residential address records during the year preceding and the year of COVID-19 diagnosis. Third, IBD was defined using ICD-10 codes from national insurance claims data, an approach that has been widely used in prior population-based studies in Korea.^[36-38] Nonetheless, misclassification remains possible, particularly for mild or early-stage disease. To address this concern, analyses were restricted to first-time diagnoses after COVID-19. Fourth, the insufficient evidence for associations with Crohn's disease compared with ulcerative colitis may be due to the smaller number of Crohn's cases (194, 436, and 102 across low, moderate, and high NDVI groups, compared with 429, 872, and 138 for ulcerative colitis) and by the longer subclinical course of Crohn's disease, which may not have been detectable within the pandemic follow-up.^[2] Fifth, several established or plausible risk factors, including dietary factors, vitamin D status, air pollution, occupational exposures, and family history of IBD were not available in the administrative data, and residual confounding cannot be excluded.^[39]

Despite these limitations, this study has several notable strengths. Using a nationwide cohort of 6,900,341 individuals with confirmed COVID-19, it is the first to evaluate the association between residential greenness and IBD in the context of the pandemic, with stratified analyses by age, sex, comorbidity, physical activity, and income. In addition, the linkage of individual-level administrative health records with satellite-derived NDVI allowed a detailed evaluation of residential greenness in relation to IBD risk.

Clinical and policy implications

Our findings suggest that residential greenness may help reduce the inflammatory response triggered by COVID-19 in IBD. The COVID-19 pandemic showed that infection-control measures such as lockdowns and mobility restrictions, while necessary, may restrict access to residential greenness, emphasizing the need to preserve such access even during public health pandemics.^[40] Evidence from several countries has shown that outdoor activities including walking, cycling, and running can be maintained safely with distancing protocols, and health agencies including the United States Centers for Disease Control and Prevention recommended keeping green spaces accessible.^[41,42] Urban planning should prioritize sustained access to residential greenness, while clinicians should encourage patients at increased risk of IBD, on the potential health benefits of natural environments as part of preventive care.^[42]

In conclusion, in this nationwide cohort study of 6,900,341 individuals with COVID-19, higher residential greenness was associated with a lower incidence of inflammatory bowel disease, with the most consistent associations observed for ulcerative colitis. These associations were more apparent among individuals with mild COVID-19, and were stronger among females, middle-aged adults, and those with pre-existing comorbidities. For Crohn's disease, associations with residential greenness were weaker and generally limited to individuals exposed to high NDVI, which may be due to its longer subclinical course and stronger genetic factors. Thus, residential environmental context may warrant consideration in the assessment of postinfectious inflammatory disease risk.

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Conflicts of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Residential greenness and inflammatory bowel disease risk after COVID-19

In 6.9 million South Korean COVID-19 survivors, higher residential greenness was associated with a 29% lower risk of new-onset inflammatory bowel disease.

6.9M

COVID-19 COHORT
South Korea · nationwide
NHIS + KDCA linkage

NDVI

SATELLITE VEGETATION INDEX
NASA Terra MODIS
MOD13A3 v6.1 · 1 km grid

Cox + IPTW

ANALYTIC METHOD
Adjusted HR · weighted
IBD ≥ 30 d post-infection

SCOPE Adults ≥ 19 y with RT-PCR-confirmed SARS-CoV-2 · follow-up 2020-2023 · NDVI tiers: low (0.2-≤0.4) · moderate (0.4-≤0.6) · high (≥ 0.6)

PRIMARY OUTCOME · HIGH vs. LOW NDVI

Incident IBD after COVID-19 infection

aHR 0.71

95% CI 0.68-0.74 · 29% relative risk reduction

ULCERATIVE COLITIS

aHR 0.60

95% CI 0.57-0.63

strongest signal · high NDVI

CROHN'S DISEASE

aHR 0.90

95% CI 0.85-0.96

weaker · high NDVI only

MODERATE vs. LOW NDVI

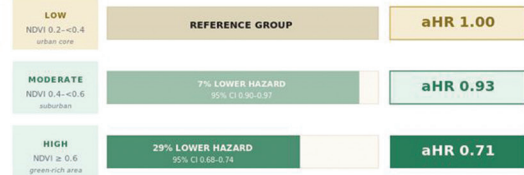
aHR 0.93

95% CI 0.90-0.97

any IBD · modest reduction

NDVI tier → adjusted hazard ratio

ANY-IBD INCIDENCE (vs. LOW NDVI REFERENCE)



Dose-response: **monotonic risk reduction** as residential greenness increases. UC drives the gradient (aHR 0.60 at high NDVI).

EFFECT MODIFIERS · STRONGER ASSOCIATIONS IN

Females

SEX SUBGROUP

40-59 y

AGE STRATUM

Comorbid

PRE-EXISTING CONDITIONS

Effect more apparent in **mild COVID-19** · consistent across income tertiles.

DESIGN · K-COV-N NATIONWIDE COHORT

Exposure: 1-km NDVI linked to home GPS

Outcome: ICD-10 K50 (CD) · K51 (UC), ≥ 30 d post-infection

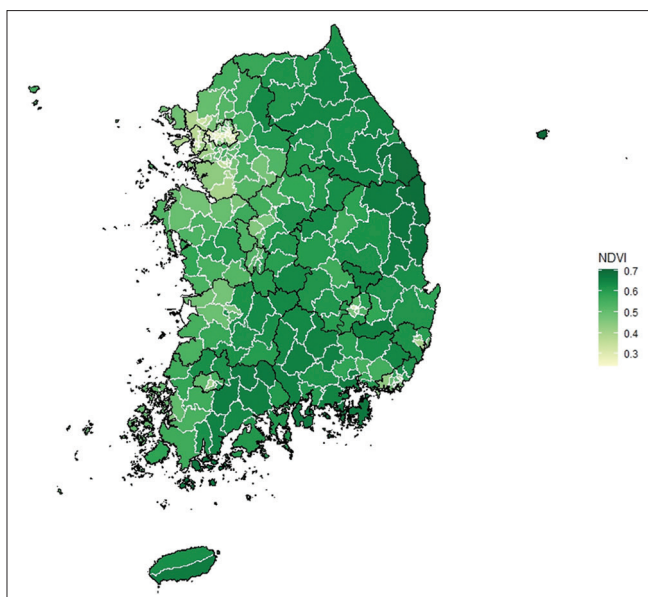
Adjustment: IPTW for age, sex, income, CCI, BMI, BP, FBG, eGFR, smoking, alcohol, physical activity

Follow-up: Jan 2020 - Dec 2023 · reverse causation minimised by 30 d washout

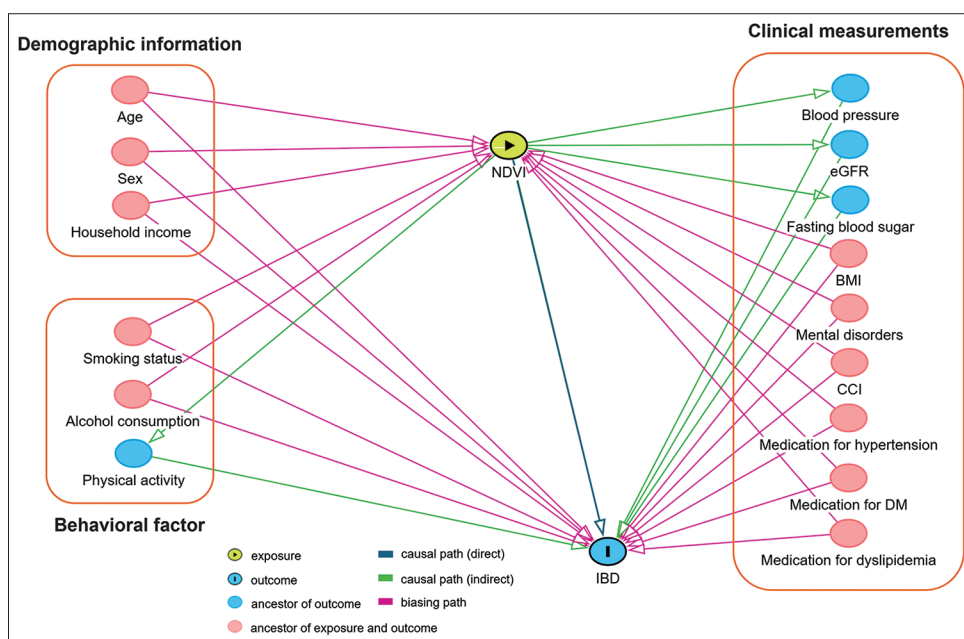
CLINICAL TAKEAWAY

Maintaining access to residential greenness during periods of restricted mobility may help counter post-COVID inflammatory bowel risk.

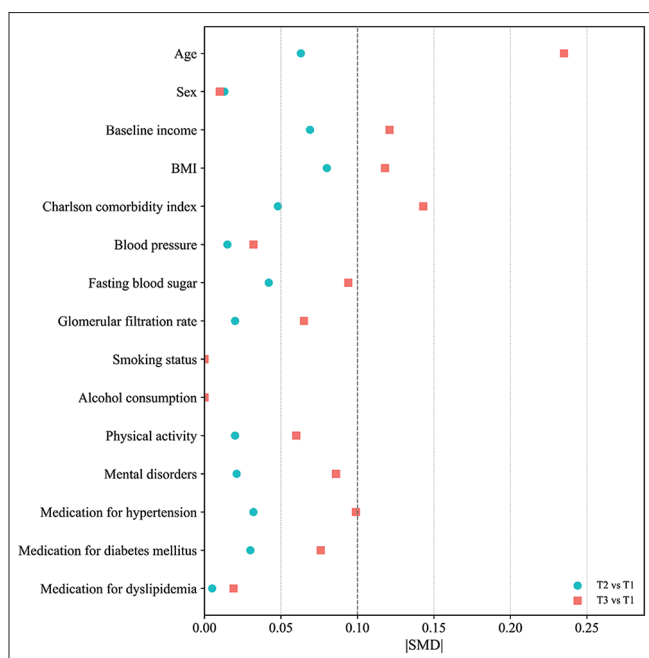
Yeo D, Kim K, Kim J, et al.
Saudi J Gastroenterol. 2026. doi:10.4103/sjg.sjg_430_25
Kyung Hee University Medical Center, Seoul



Supplementary Figure 1: Spatial distribution of NDVI across South Korea. Abbreviations: NDVI, normalized difference vegetation index



Supplementary Figure 2: A direct acyclic graph of the hypothesized causal pathways between NDVI and inflammatory bowel disease. Abbreviations: BMI, body mass index; CCI, Charlson comorbidity index; CI, confidence interval; DM, diabetes mellitus; IBD, inflammatory bowel disease; NDVI, normalized difference vegetation index



Supplementary Figure 3: Standardized mean differences after 1:1:1 IPTW propensity score weighting. Abbreviations: SMD, standardized mean difference. SMD < 0.1 indicates no major imbalance.

Supplementary Table 1: Cohort characteristics before IPTW weighting (n=6,900,341)

Baseline characteristic	T1	T2	T3
Total	1,761,608	4,109,759	1,028,974
Age (y), mean±SD	46.34±13.68	47.20±13.75	49.59±14.03
Sex, n (%)			
Men	991,406 (56.28)	2,340,005 (56.94)	584,088 (56.76)
Women	770,202 (43.72)	1,769,754 (43.06)	444,886 (43.24)
Baseline income, n (%)			
Q1	494,105 (28.05)	1,237,388 (30.11)	331,452 (32.21)
Q2	741,210 (42.08)	1,757,945 (42.77)	438,013 (42.57)
Q3	526,293 (29.88)	1,114,426 (27.12)	259,509 (25.22)
BMI, n (%)			
Underweight	62,302 (3.54)	129,573 (3.15)	27,744 (2.70)
Normal	610,448 (34.65)	1,366,457 (33.25)	323,482 (31.44)
Overweight	399,713 (22.69)	939,757 (22.87)	240,522 (23.37)
Obesity	689,145 (39.12)	1,673,972 (40.73)	437,226 (42.49)
Charlson comorbidity index, n (%)			
0	1,626,592 (92.34)	3,731,440 (90.79)	903,953 (87.85)
1	72,802 (4.13)	212,276 (5.17)	71,822 (6.98)
≥2	62,214 (3.53)	166,043 (4.04)	53,199 (5.17)
Blood pressure, n (%)			
SBP<140 and DBP<90	1,546,681 (87.80)	3,587,435 (87.29)	892,534 (86.74)
SBP≥140 or DBP≥90	214,927 (12.20)	522,324 (12.71)	136,440 (13.26)
Fasting blood sugar, n (%)			
<100 mg/dL	1,138,025 (64.60)	2,572,410 (62.59)	618,158 (60.08)
≥100 mg/dL	623,583 (35.40)	1,537,349 (37.41)	410,816 (39.92)
Glomerular filtration rate, n (%)			
<60mL/min/1.73 m ²	39,848 (2.26)	99,540 (2.42)	28,623 (2.78)
≥60mL/min/1.73 m ²	1,721,760 (97.74)	4,010,219 (97.57)	1,000,351 (97.22)
Smoking status, n (%)			
Never	1,743,707 (98.98)	4,069,953 (99.03)	1,019,426 (99.07)
Former/Current	17,256 (0.98)	37,931 (0.92)	9,011 (0.88)
Unknown	645 (0.04)	1875 (0.05)	537 (0.05)
Alcohol consumption, n (%)			
<1 days/week	1,034,185 (58.71)	2,481,684 (60.39)	638,104 (62.01)
1-2 days/week	512,196 (29.08)	1,141,352 (27.77)	267,225 (25.97)
3-4 days/week	168,642 (9.57)	376,976 (9.17)	93,121 (9.05)
≥5 days/week	45,978 (2.61)	107,860 (2.62)	29,893 (2.91)
Unknown	607 (0.03)	1887 (0.05)	631 (0.06)
Physical activity, n (%)			
Insufficient	837,432 (47.54)	1,948,955 (47.42)	466,130 (45.30)
Sufficient	923,536 (52.43)	2,158,834 (52.53)	562,270 (54.64)
Unknown	640 (0.04)	1970 (0.05)	574 (0.06)
Mental disorders, n (%)			
No	1,445,564 (82.06)	3,339,669 (81.26)	809,080 (78.63)
Yes	316,044 (17.94)	770,090 (18.74)	219,894 (21.37)
Medication for hypertension, n (%)			
No	1,499,218 (85.11)	3,450,295 (83.95)	837,517 (81.39)
Yes	262,390 (14.89)	659,464 (16.05)	191,457 (18.61)
Medication for diabetes mellites, n (%)			
No	1,651,900 (93.77)	3,823,613 (93.04)	944,821 (91.82)
Yes	109,708 (6.23)	286,146 (6.96)	84,153 (8.18)
Medication for dyslipidemia, n (%)			
No	1,618,669 (91.89)	3,770,790 (91.75)	940,222 (91.37)
Yes	142,939 (8.11)	338,969 (8.25)	88,752 (8.63)

BMI, Body mass index; IPTW, inverse probability of treatment weighting; SD, standard deviation; SMD, Standardized mean difference; T1, low NDVI group; T2, medium NDVI group; T3, high NDVI group

Supplementary Table 2: Association between NDVI and incident IBD outcomes across alternative latency windows (30, 90, and 180 days)

	aHR (95% CI)		
	30 days	90 days	180 days
Inflammatory Bowel Disease			
Low NDVI	1.00 (reference)	1.00 (reference)	1.00 (reference)
Moderate NDVI	0.93 (0.90 to 0.97)	0.93 (0.90 to 0.97)	0.93 (0.90 to 0.97)
High NDVI	0.71 (0.68 to 0.74)	0.71 (0.68 to 0.74)	0.70 (0.67 to 0.73)
Crohn's disease			
Low NDVI	1.00 (reference)	1.00 (reference)	1.00 (reference)
Moderate NDVI	0.96 (0.90 to 1.03)	0.96 (0.90 to 1.03)	0.96 (0.90 to 1.03)
High NDVI	0.90 (0.85 to 0.96)	0.90 (0.85 to 0.97)	0.92 (0.86 to 0.98)
Ulcerative colitis			
Low NDVI	1.00 (reference)	1.00 (reference)	1.00 (reference)
Moderate NDVI	0.91 (0.87 to 0.96)	0.91 (0.86 to 0.95)	0.91 (0.87 to 0.96)
High NDVI	0.60 (0.57 to 0.63)	0.60 (0.58 to 0.64)	0.58 (0.55 to 0.62)

Model adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. CI, confidence interval; aHR, adjusted hazard ratios; NDVI, normalized difference vegetation index. Bolded values indicate statistically significant differences ($P < 0.05$)

Supplementary Table 3: Association between residential NDVI and the incidence of inflammatory bowel disease, stratified by covid severity after COVID-19

	Total	Event	Person-years	Incidence rate ^a	HR (95% CI)	
					Model 1 ^b	Model 2 ^c
Inflammatory Bowel Disease						
Mild						
Low NDVI	1,752,285	1327	2,621,520	0.507	1.00 (reference)	1.00 (reference)
Moderate NDVI	4,088,784	2859	6,017,715	0.475	0.94 (0.90 to 0.97)	0.93 (0.90 to 0.97)
High NDVI	1023777	531	1496462	0.361	0.71 (0.68 to 0.74)	0.71 (0.68 to 0.74)
Moderate-to-severe						
Low NDVI	2,578	4	3,035	1.329	1.00 (reference)	1.00 (reference)
Moderate NDVI	6,240	7	6,933	1.016	0.77 (0.37 to 1.60)	0.81 (0.39 to 1.67)
High NDVI	2103	1	2290.623	0.465	0.37 (0.14 to 0.96)	0.39 (0.15 to 1.00)
Crohn's disease						
Mild						
Low NDVI	1,756,880	491	2,628,984	0.184	1.00 (reference)	1.00 (reference)
Moderate NDVI	4,098,597	1083	6,033,377	0.179	0.97 (0.91 to 1.03)	0.97 (0.91 to 1.03)
High NDVI	1025702	244	1499481	0.169	0.91 (0.85 to 0.97)	0.90 (0.85 to 0.96)
Moderate-to-severe						
Low NDVI	2,586	2	3,047	0.626	1.00 (reference)	1.00 (reference)
Moderate NDVI	6,261	2	6,964	0.289	0.47 (0.13 to 1.63)	0.46 (0.13 to 1.66)
High NDVI	2,108	1	2,295	0.464	0.89 (0.31 to 2.61)	0.89 (0.30 to 2.64)
Ulcerative colitis						
Mild						
Low NDVI	1,754,344	869	2,624,908	0.334	1.00 (reference)	1.00 (reference)
Moderate NDVI	4,093,443	1834	6,025,246	0.305	0.91 (0.87 to 0.96)	0.91 (0.87 to 0.96)
High NDVI	1,024,892	301	1,498,256	0.202	0.61 (0.57 to 0.64)	0.60 (0.57 to 0.64)
Moderate-to-severe						
Low NDVI	2,584	2	3,042	0.699	1.00 (reference)	1.00 (reference)
Moderate NDVI	6,248	5	6,944	0.725	1.03 (0.41 to 2.57)	1.11 (0.44 to 2.81)
High NDVI	2,108	0	2,297	0	NA	NA

COVID-19, coronavirus disease 2019; CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (P -value < 0.05)

Supplementary Table 4: Association between residential NDVI and the incidence of inflammatory bowel disease, stratified by type of COVID-19 after COVID-19

	Total	Event	Person-years	Incidence rate ^a	HR (95% CI)	
					Model 1 ^b	Model 2 ^c
Inflammatory Bowel Disease						
Original strain					1.00 (reference)	1.00 (reference)
Low NDVI	10,808	16	29,578	0.542	0.82 (0.55 to 1.21)	0.83 (0.56 to 1.24)
Moderate NDVI	20,038	24	54,448	0.44	0.61 (0.38 to 0.98)	0.63 (0.39 to 1.01)
High NDVI	4025	4	10917.49	0.326		
Delta						
Low NDVI	26610	23	56509.64	0.401	1.00 (reference)	1.00 (reference)
Moderate NDVI	43423	56	92528.12	0.605	1.53 (1.14 to 2.04)	1.54 (1.15 to 2.05)
High NDVI	7165	6	15226.44	0.425	1.07 (0.75 to 1.55)	1.09 (0.75 to 1.56)
Omicron						
Low NDVI	1,717,445	1292	2,538,467	0.51	1.00 (reference)	1.00 (reference)
Moderate NDVI	4,031,563	2786	5,877,671	0.474	0.93 (0.89 to 0.97)	0.93 (0.89 to 0.96)
High NDVI	1,014,690	522	1,472,609	0.361	0.71 (0.68 to 0.74)	0.70 (0.67 to 0.73)
Crohn's disease						
Original strain						
Low NDVI	10,838	5	29,678	0.168	1.00 (reference)	1.00 (reference)
Moderate NDVI	20,106	11	54,659	0.201	1.18 (0.62 to 2.22)	1.20 (0.64 to 2.27)
High NDVI	4,030	1	10,937	0.079	0.46 (0.18 to 1.17)	0.48 (0.19 to 1.24)
Delta						
Low NDVI	26,682	4	56,687	0.068	1.00 (reference)	1.00 (reference)
Moderate NDVI	43,515	21	92,764	0.225	3.09 (1.70 to 5.61)	3.15 (1.74 to 5.73)
High NDVI	7,178	2	15,257	0.166	2.24 (1.12 to 4.48)	2.32 (1.16 to 4.65)
Omicron						
Low NDVI	1,721,946	484	2,545,666	0.188	1.00 (reference)	1.00 (reference)
Moderate NDVI	4,041,237	1053	5,892,918	0.178	0.95 (0.89 to 1.01)	0.94 (0.88 to 1.01)
High NDVI	1,016,602	242	1,475,582	0.17	0.90 (0.84 to 0.96)	0.89 (0.84 to 0.96)
Ulcerative colitis						
Original strain						
Low NDVI	10,817	12	29,611	0.404	1.00 (reference)	1.00 (reference)
Moderate NDVI	20,055	15	54,505	0.274	0.69 (0.42 to 1.11)	0.69 (0.43 to 1.13)
High NDVI	4,027	3	10,924	0.247	0.62 (0.36 to 1.07)	0.64 (0.37 to 1.10)
Delta						
Low NDVI	26,637	19	56,569	0.332	1.00 (reference)	1.00 (reference)
Moderate NDVI	43,448	36	92,599	0.389	1.21 (0.86 to 1.69)	1.22 (0.87 to 1.71)
High NDVI	7,175	5	15,248	0.348	1.08 (0.72 to 1.62)	1.10 (0.74 to 1.65)
Omicron						
Low NDVI	1,719,474	840	2,541,770	0.334	1.00 (reference)	1.00 (reference)
Moderate NDVI	4,036,188	1788	5,885,086	0.304	0.91 (0.87 to 0.96)	0.91 (0.87 to 0.96)
High NDVI	1,015,798	293	1,474,381	0.2	0.60 (0.57 to 0.63)	0.60 (0.56 to 0.63)

COVID-19, coronavirus disease 2019; CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (p-value<0.05)

Supplementary Table 5: Association between residential NDVI and the incidence of inflammatory bowel disease, stratified by sex after COVID-19

	Total	Event	Person-years	Incidence rate ^a	HR (95% CI)	
					Model 1 ^b	Model 2 ^c
Inflammatory Bowel Disease						
Male						
Low NDVI	986,952	848	1,479,221	0.572	1.00 (reference)	1.00 (reference)
Moderate NDVI	2,329,969	1,854	3,424,779	0.541	0.94 (0.90 to 0.99)	0.94 (0.89 to 0.99)
High NDVI	581,993	331	846,834	0.4	0.70 (0.66 to 0.73)	0.69 (0.65 to 0.73)
Female						
Low NDVI	767,911	483	1,145,333	0.424	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,765,055	1,012	2,599,869	0.389	0.92 (0.86 to 0.98)	0.92 (0.86 to 0.98)
High NDVI	443,887	201	651,919	0.31	0.73 (0.68 to 0.79)	0.73 (0.68 to 0.79)
Crohn's disease						
Male						
Low NDVI	989,972	306	1,484,120	0.203	1.00 (reference)	1.00 (reference)
Moderate NDVI	2,336,598	660	3,435,374	0.192	0.93 (0.86 to 1.01)	0.93 (0.86 to 1.01)
High NDVI	583,328	152	848,903	0.188	0.91 (0.84 to 0.99)	0.90 (0.83 to 0.98)
Female						
Low NDVI	769,494	187	1,147,911	0.161	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,768,260	425	2,604,967	0.163	1.02 (0.92 to 1.13)	1.02 (0.92 to 1.13)
High NDVI	444,482	93	652,872	0.145	0.90 (0.81 to 1.00)	0.90 (0.81 to 1.00)
Ulcerative colitis						
Male						
Low NDVI	988,328	569	1,481,474	0.385	1.00 (reference)	1.00 (reference)
Moderate NDVI	2,333,198	1,233	3,429,924	0.36	0.93 (0.88 to 0.99)	0.93 (0.88 to 0.99)
High NDVI	582,722	188	848,005	0.223	0.58 (0.54 to 0.62)	0.57 (0.54 to 0.61)
Female						
Low NDVI	768,600	302	1,146,476	0.268	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,766,493	606	2,602,266	0.233	0.87 (0.80 to 0.95)	0.87 (0.80 to 0.95)
High NDVI	444,278	113	652,548	0.173	0.65 (0.59 to 0.71)	0.65 (0.59 to 0.71)

COVID-19, coronavirus disease 2019; CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (p-value<0.05)

Supplementary Table 6: Association between residential NDVI and the incidence of inflammatory bowel disease, stratified by age group after COVID-19

	Total	Event	Person-years	Incidence rate ^a	HR (95% CI)	
					Model 1 ^b	Model 2 ^c
Inflammatory Bowel Disease						
19–39 years						
Low NDVI	615,079	524	928,083	0.564	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,301,900	1045	1,943,672	0.537	0.95 (0.89 to 1.01)	0.95 (0.89 to 1.01)
High NDVI	267,607	182	399,013	0.469	0.83 (0.77 to 0.88)	0.83 (0.78 to 0.89)
40–59 years						
Low NDVI	768,255	533	1,156,853	0.464	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,856,719	1144	2,755,352	0.415	0.90 (0.84 to 0.96)	0.89 (0.84 to 0.95)
High NDVI	454,013	182	670,940	0.268	0.58 (0.54 to 0.62)	0.58 (0.54 to 0.62)
≥60 years						
Low NDVI	371,529	274	539,619	0.514	1.00 (reference)	1.00 (reference)
Moderate NDVI	936,405	677	1,325,624	0.511	1.00 (0.92 to 1.08)	0.99 (0.92 to 1.08)
High NDVI	304,260	168	428,800	0.388	0.76 (0.70 to 0.83)	0.76 (0.69 to 0.82)
Crohn's disease						
19–39 years						
Low NDVI	616,395	238	930,275	0.255	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,304,359	497	1,947,725	0.255	1.00 (0.90 to 1.10)	1.00 (0.91 to 1.10)
High NDVI	268,106	103	399,819	0.264	1.03 (0.94 to 1.13)	1.03 (0.94 to 1.14)
40–59 years						
Low NDVI	770,210	180	1,160,069	0.156	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,861,152	403	2,762,477	0.146	0.94 (0.85 to 1.04)	0.94 (0.84 to 1.04)
High NDVI	454,777	75	672,155	0.11	0.71 (0.63 to 0.79)	0.70 (0.63 to 0.79)
≥60 years						
Low NDVI	372,861	75	541,688	0.142	1.00 (reference)	1.00 (reference)
Moderate NDVI	939,347	185	1,330,140	0.139	0.98 (0.84 to 1.15)	0.97 (0.83 to 1.13)
High NDVI	304,927	67	429,802	0.15	1.06 (0.91 to 1.23)	1.04 (0.90 to 1.21)
Ulcerative colitis						
19–39 years						
Low NDVI	616,166	307	929,865	0.33	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,304,203	572	1,947,422	0.293	0.88 (0.81 to 0.96)	0.89 (0.81 to 0.97)
High NDVI	268,054	86	399,753	0.222	0.67 (0.61 to 0.73)	0.67 (0.61 to 0.74)
40–59 years						
Low NDVI	768,996	361	1,158,080	0.314	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,858,390	768	2,758,053	0.278	0.89 (0.82 to 0.96)	0.89 (0.82 to 0.95)
High NDVI	454,440	112	671,623	0.165	0.53 (0.48 to 0.58)	0.52 (0.48 to 0.57)
≥60 years						
Low NDVI	371,766	203	540,005	0.38	1.00 (reference)	1.00 (reference)
Moderate NDVI	937,098	499	1,326,714	0.376	1.00 (0.91 to 1.10)	1.00 (0.91 to 1.09)
High NDVI	304,506	103	429,176	0.243	0.65 (0.58 to 0.72)	0.64 (0.58 to 0.72)

COVID-19, coronavirus disease 2019; CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (p-value<0.05)

Supplementary Table 7: Association between residential NDVI and the incidence of inflammatory bowel disease, stratified by CCI after COVID-19.

	Total	Event	Person-years	Incidence rate ^a	HR (95% CI)	
					Model 1 ^b	Model 2 ^c
Inflammatory Bowel Disease						
CCI 0						
Low NDVI	1,620,543	1192	2,427,078	0.489	1.00 (reference)	1.00 (reference)
Moderate NDVI	3,718,462	2524	5,483,734	0.46	0.94 (0.90 to 0.98)	0.94 (0.90 to 0.98)
High NDVI	901,322	448	1,322,022	0.349	0.71 (0.68 to 0.75)	0.71 (0.68 to 0.74)
CCI 1+						
Low NDVI	134,320	139	197,477	0.704	1.00 (reference)	1.00 (reference)
Moderate NDVI	376,562	342	540,914	0.632	0.90 (0.80 to 1.00)	0.90 (0.80 to 1.00)
High NDVI	124,558	84	176,730	0.479	0.68 (0.60 to 0.76)	0.68 (0.60 to 0.76)
Crohn's disease						
CCI 0						
Low NDVI	1,624,673	443	2,433,797	0.179	1.00 (reference)	1.00 (reference)
Moderate NDVI	3,727,142	960	5,497,613	0.174	0.97 (0.91 to 1.04)	0.97 (0.91 to 1.04)
High NDVI	902,968	209	1,324,610	0.166	0.92 (0.86 to 0.98)	0.92 (0.86 to 0.98)
CCI 1+						
Low NDVI	134,793	50	198,234	0.244	1.00 (reference)	1.00 (reference)
Moderate NDVI	377,716	125	542,729	0.23	0.93 (0.77 to 1.13)	0.93 (0.77 to 1.12)
High NDVI	124,842	36	177,165	0.202	0.82 (0.67 to 0.99)	0.81 (0.67 to 0.99)
Ulcerative colitis						
CCI 0						
Low NDVI	1,622,394	778	2,430,124	0.32	1.00 (reference)	1.00 (reference)
Moderate NDVI	3,722,558	1617	5,490,366	0.295	0.92 (0.87 to 0.97)	0.92 (0.87 to 0.97)
High NDVI	902,271	252	1,323,556	0.193	0.60 (0.57 to 0.64)	0.60 (0.57 to 0.64)
CCI 1+						
Low NDVI	134,534	93	197,825	0.477	1.00 (reference)	1.00 (reference)
Moderate NDVI	377,133	222	541,824	0.41	0.86 (0.75 to 0.99)	0.86 (0.75 to 0.99)
High NDVI	124,729	49	176,996	0.283	0.59 (0.51 to 0.69)	0.59 (0.51 to 0.69)

COVID-19, coronavirus disease 2019; CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (p-value<0.05)

Supplementary Table 8: Association between residential NDVI and the incidence of inflammatory bowel disease, stratified by physical activity after COVID-19

	Total	Event	Person-years	Incidence rate ^a	HR (95% CI)	
					Model 1 ^b	Model 2 ^c
Inflammatory Bowel Disease						
Insufficient						
Low NDVI	834,289	639	1,247,497	0.509	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,941,965	1353	2,858,442	0.473	0.93 (0.88 to 0.98)	0.93 (0.87 to 0.98)
High NDVI	464,760	231	679,222	0.341	0.67 (0.63 to 0.72)	0.67 (0.63 to 0.71)
Sufficient						
Low NDVI	919,935	692	1,376,041	0.507	1.00 (reference)	1.00 (reference)
Moderate NDVI	2,151,096	1512	3,163,143	0.478	0.94 (0.89 to 0.99)	0.94 (0.89 to 0.99)
High NDVI	560,549	301	818,655	0.378	0.74 (0.70 to 0.78)	0.74 (0.70 to 0.78)
Crohn's disease						
Insufficient						
Low NDVI	836,429	250	1,250,975	0.197	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,946,563	531	2,865,780	0.185	0.94 (0.85 to 1.02)	0.93 (0.85 to 1.02)
High NDVI	465,618	112	680,567	0.166	0.84 (0.77 to 0.93)	0.83 (0.76 to 0.92)
Sufficient						
Low NDVI	922,397	243	1,380,038	0.174	1.00 (reference)	1.00 (reference)
Moderate NDVI	2,156,325	553	3,171,487	0.174	1.00 (0.91 to 1.09)	0.99 (0.91 to 1.09)
High NDVI	561,618	133	820,328	0.172	0.97 (0.89 to 1.07)	0.97 (0.89 to 1.06)
Ulcerative colitis						
Insufficient						
Low NDVI	835,263	406	1,249,129	0.325	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,944,227	846	2,862,111	0.296	0.91 (0.85 to 0.98)	0.91 (0.85 to 0.98)
High NDVI	465,251	124	680,012	0.182	0.56 (0.52 to 0.61)	0.56 (0.51 to 0.61)
Sufficient						
Low NDVI	921,026	465	1,377,805	0.343	1.00 (reference)	1.00 (reference)
Moderate NDVI	2,153,501	993	3,167,015	0.314	0.91 (0.86 to 0.98)	0.91 (0.85 to 0.98)
High NDVI	561,178	177	819,664	0.218	0.63 (0.59 to 0.68)	0.63 (0.59 to 0.68)

COVID-19, coronavirus disease 2019; CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (p-value<0.05)

Supplementary Table 9: Association between residential NDVI and the incidence of inflammatory bowel disease, stratified by baseline income after COVID-19

	Total	Event	Person-years	Incidence rate ^a	HR (95% CI)	
					Model 1 ^b	Model 2 ^c
Inflammatory Bowel Disease						
Low income						
Low NDVI	492,383	363	736,970	0.496	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,233,230	882	1,814,592	0.486	0.98 (0.92 to 1.06)	0.98 (0.91 to 1.05)
High NDVI	330,534	169	483,027	0.355	0.72 (0.66 to 0.78)	0.71 (0.66 to 0.77)
Middle income						
Low NDVI	738,318	574	1,106,618	0.521	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,751,569	1235	2,584,175	0.478	0.91 (0.86 to 0.97)	0.91 (0.86 to 0.97)
High NDVI	436,635	218	640,151	0.346	0.66 (0.62 to 0.70)	0.66 (0.62 to 0.70)
High income						
Low NDVI	524,162	394	780,967	0.502	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,110,225	749	1,625,881	0.461	0.92 (0.86 to 0.99)	0.92 (0.85 to 0.99)
High NDVI	258,711	145	375,575	0.392	0.79 (0.73 to 0.86)	0.78 (0.72 to 0.84)
Crohn's disease						
Low income						
Low NDVI	493,552	131	738,867	0.174	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,235,908	351	1,818,898	0.192	1.10 (0.98 to 1.23)	1.09 (0.97 to 1.23)
High NDVI	331,067	84	483,862	0.179	1.00 (0.89 to 1.13)	1.00 (0.89 to 1.13)
Middle income						
Low NDVI	740,222	231	1,109,714	0.207	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,755,696	473	2,590,843	0.182	0.88 (0.80 to 0.97)	0.87 (0.79 to 0.96)
High NDVI	437,487	101	641,487	0.166	0.80 (0.72 to 0.88)	0.79 (0.72 to 0.88)
High income						
Low NDVI	525,692	131	783,450	0.164	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,113,254	261	1,630,600	0.16	0.98 (0.86 to 1.12)	0.98 (0.86 to 1.12)
High NDVI	259,256	60	376,426	0.163	1.01 (0.89 to 1.16)	1.01 (0.88 to 1.15)
Ulcerative colitis						
Low income						
Low NDVI	492,912	238	737,841	0.329	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,234,640	557	1,816,871	0.307	0.95 (0.86 to 1.03)	0.94 (0.86 to 1.03)
High NDVI	330,903	89	483,606	0.186	0.58 (0.52 to 0.64)	0.57 (0.52 to 0.63)
Middle income						
Low NDVI	739,272	361	1,108,187	0.329	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,753,720	784	2,587,650	0.303	0.92 (0.85 to 0.99)	0.91 (0.85 to 0.99)
High NDVI	437,141	125	640,963	0.192	0.58 (0.53 to 0.63)	0.58 (0.53 to 0.63)
High income						
Low NDVI	524,744	272	781,922	0.348	1.00 (reference)	1.00 (reference)
Moderate NDVI	1,111,331	498	1,627,669	0.306	0.88 (0.80 to 0.97)	0.88 (0.80 to 0.96)
High NDVI	258,956	87	375,984	0.234	0.68 (0.61 to 0.75)	0.66 (0.60 to 0.73)

COVID-19, coronavirus disease 2019; CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (p-value<0.05)

Supplementary Table 10: Association between residential NDVI and the incidence of inflammatory bowel disease, stratified by mental disorders after COVID-19

	Total	Event	Person-years	Incidence rate ^a	HR (95% CI)	
					Model 1 ^b	Model 2 ^c
Inflammatory Bowel Disease						
Yes						
Low NDVI	1,440,291	1047	2,168,818	0.481	1.00 (reference)	1.00 (reference)
Moderate NDVI	3,328,180	2248	4,934,544	0.455	0.90 (0.83 to 0.98)	0.90 (0.83 to 0.98)
High NDVI	806,757	396	1,188,146	0.341	0.71 (0.65 to 0.78)	0.71 (0.65 to 0.78)
No						
Low NDVI	314,572	284	455,736	0.627	1.00 (reference)	1.00 (reference)
Moderate NDVI	766,844	618	1,090,104	0.567	0.94 (0.90 to 0.99)	0.94 (0.90 to 0.98)
High NDVI	219123	136	310607.1	0.449	0.71 (0.67 to 0.74)	0.70 (0.67 to 0.74)
Crohn's disease						
Yes						
Low NDVI	1,443,868	386	2,174,677	0.175	1.00 (reference)	1.00 (reference)
Moderate NDVI	3,335,828	850	4,946,891	0.171	0.93 (0.81 to 1.06)	0.93 (0.81 to 1.06)
High NDVI	808,210	180	1,190,440	0.159	0.93 (0.81 to 1.07)	0.93 (0.81 to 1.06)
No						
Low NDVI	315,598	107	457,354	0.232	1.00 (reference)	1.00 (reference)
Moderate NDVI	769,030	235	1,093,450	0.214	0.98 (0.91 to 1.05)	0.97 (0.90 to 1.05)
High NDVI	219,600	65	311,336	0.215	0.90 (0.84 to 0.97)	0.89 (0.83 to 0.96)
Ulcerative colitis						
Yes						
Low NDVI	1,441,935	687	2,171,533	0.318	1.00 (reference)	1.00 (reference)
Moderate NDVI	3,331,839	1445	4,940,516	0.292	0.88 (0.79 to 0.98)	0.88 (0.79 to 0.97)
High NDVI	807,596	229	1,189,496	0.194	0.57 (0.51 to 0.65)	0.57 (0.51 to 0.64)
No						
Low NDVI	314,993	184	456,417	0.41	1.00 (reference)	1.00 (reference)
Moderate NDVI	767,852	394	1,091,674	0.362	0.92 (0.87 to 0.97)	0.92 (0.87 to 0.97)
High NDVI	219,404	72	311,057	0.237	0.61 (0.58 to 0.65)	0.61 (0.57 to 0.65)

COVID-19, coronavirus disease 2019; CI, confidence interval; HR, hazard ratios; NDVI, normalized difference vegetation index. ^aIncidence rate is expressed as per 1,000 person-years. ^bModel 1: adjusted for age, and sex. ^cModel 2: adjusted for age, sex, household income, Body mass index, blood pressure, fasting blood glucose levels, estimated glomerular filtration rate, Charlson comorbidity index, mental disorder, history of antihypertensive medications/diabetes/dyslipidemia, smoking status, weekly alcohol consumption frequency, and aerobic physical activity level. Bolded values indicate statistically significant differences (p-value<0.05)