Supplementary Information

Text S1. Measurement of soil physicochemical properties: The main indicators of soil physicochemical properties included pH, electrical conductivity (EC), total carbon (TC), total nitrogen (TN), ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), organic matter (OM), available phosphorus (AP), and available potassium (AK). Soil pH and EC were measured using a pH meter and a conductivity meter, respectively. AP and AK were determined using commercial assay kits (SH898 and SH899, respectively). OM determination method: Soils were pretreated with hydrochloric acid to remove carbonates. Subsequently, a carbon-nitrogen analyzer (Vario EL, Elementar, Hanau, Germany) was used to measure TC, TN, and organic carbon (OC) contents. OM was then calculated by converting OC values using the van Bemmelen factor (1.724). NH_4^+-N and NO_3^--N were determined according to the national standard GB/T 32737-2016.

Text S2. Chlorophyll content determination: Fresh leaf tissues were thoroughly ground in liquid nitrogen, and 40 mg of the ground sample was transferred to a 4 mL solution of 80% acetone and mixed well. The mixture was incubated at 68 ℃ in a water bath for 15 minutes, followed by cooling to room temperature. Afterward, the sample was centrifuged at 4000 g for 15 minutes. A 200 μL aliquot of the supernatant was then transferred to a microplate, and the absorbance was measured at wavelengths of 663 nm and 646 nm using a microplate reader. Chlorophyll concentrations (mg/L) were calculated using the following equations:

$$\text{Chlorophyll a} = 12.21A_{663} - 2.81A_{646}$$

$$\text{Chlorophyll b} = 20.13A_{646} - 5.03A_{663}$$

Text S3. Similar to the approach used with different concentrations of CeO_2 NMs, the optimal concentration for seed germination was first identified across different soil types. Subsequently, treatments with $CeCl_3$ and bulk CeO_2, containing an equivalent amount of Ce as the optimal concentration, were selected. For each treatment, 11 g of fresh soil was weighed into a 50 mL centrifuge tube. Then, 5.5 mL of the respective solutions/suspensions of $CeCl_3$, bulk CeO_2, and CeO_2 NMs (each with equivalent Ce content) were added and thoroughly mixed with the soil. The mixture was left to settle for one day. Following this, 20 mL of sterile phosphate-buffered saline (PBS) was added to each tube. The tubes were shaken at 25 ℃ and 200 rpm for 1 hour. The PBS-microbial suspension was then centrifuged at a low speed (600 g) for 4 minutes to separate larger soil particles. After centrifugation, 10 mL of the supernatant was transferred into a Petri dish. Wheat seeds, previously surface-sterilized with 5% NaClO, were also placed in the Petri dish. Seed germination and seedling growth experiments were conducted under conditions similar to those used for the different concentrations of CeO_2 NMs.

Text S4. Instrument Operating Parameters and Data Analysis. The instrument operating parameters were divided into liquid chromatography (LC) and mass spectrometry (MS) settings. LC Parameters:An injection volume of 6 μL was used. The chromatographic column was maintained at 40 ℃ throughout the run. Mobile phase A consisted of 0.1% (v/v) formic acid in water, and mobile phase B was 0.1% (v/v) formic acid in acetonitrile. The linear gradient elution was programmed as

follows: 0 min, 5% B; 1.5 min, 5% B; 10 min, 100% B; 11 min, 100% B; 11.5 min, 5% B; 14 min, 5% B. The flow rate was set to 0.35 mL/min. MS Parameters: Compounds were detected in both positive and negative ion modes using a quadrupole time–of–flight (Q-TOF) mass spectrometer equipped with an Apollo II electrospray ionization (ESI) source (Bruker Daltonics, USA). The capillary voltage was + 3.0 kV (-3.0 kV), sampling cone voltage +40 V (-23 V), source temperature 120 ℃, and desolvation temperature 350 ℃. Collision energy ranged from 10 to 40 V, ion energy was 1 V. The scan time was 0.03 s (positive mode) and 0.02 s (negative mode), with a scan range of m/z 70-1050. To ensure data quality, quality control (QC) sample was injected after every five sample injections during the entire analysis process.Data Preprocessing and Statistical Analysis: Raw data files were processed using Compound Discoverer 3.1 (Thermo Fisher Scientific) based on mzCloud and S-7 ChemSpider databases. Principal component analysis (PCA) and supervised methods such as partial least squares discriminant analysis (PLS-DA) were performed using MetaboAnalyst 5.0 (http://www.metaboanalyst.ca/). Prior to statistical analysis, all data were log-transformed and normalized. Significantly altered metabolites were identified by univariate statistical analysis with a fold change (FC) > 2 and $p < 0.05$.

Text S5. Coomassie brilliant blue method for soluble protein determination. First, 100 mg of Coomassie brilliant blue G-250 was dissolved in 50 mL of 95% ethanol, followed by the addition of 100 mL of 85% phosphoric acid. The mixture was then diluted to a final volume of 1 L with deionized water to prepare the dye reagent.A total of 0.2 g of liquid nitrogen-ground wheat seed sample was

homogenized with 2 mL of deionized water. The homogenate was centrifuged at 12,000 rpm for 10 minutes at 4 ℃. Then, 0.1 mL of the supernatant was mixed with 4.9 mL of Coomassie brilliant blue reagent in a centrifuge tube. The absorbance was measured at 595 nm using a spectrophotometer to determine the protein concentration. A standard curve was generated using bovine serum albumin (BSA) at concentrations of 0, 10, 20, 50, and 100 μg/mL. These standards were treated identically to the seed samples, and their absorbance at 595 nm was used to construct the calibration curve.The soluble protein content was calculated using the following formula.

$$\text{Soluble protein content (mg/g)} = (C \times V / a) / W$$

C : protein concentration obtained from the standard curve (μg)

V : total volume of the extract (mL)

a : volume of extract used for measurement (mL)

W : sample fresh weight (g)

Text S6. Seed metabolome analysis. Briefly, 100 mg of thoroughly liquid nitrogen-ground wheat seeds were weighed and placed in a 2 mL centrifuge tube. Then, 1.5 mL of 80% methanol aqueous solution containing 0.1% formic acid and 0.2 mg of 2-chloro-l-phenylalanine as an internal standard was added. The mixture was vortexed thoroughly and subjected to ice-bath ultrasonication (30 min, 35 kHz). Subsequently, the mixture was centrifuged at 4 ℃ and 12,000 rpm for 15 min. The supernatant was collected and vacuum-dried using a rotary evaporator (connected to a cold trap). The residue was redissolved in 200 μL of methanol-acetonitrile-water (4:4:2, v/v/v), followed by centrifugation at 4 ℃ and 12,000 rpm for 10 min to collect

the supernatant (120 μL). Equal volumes of each sample were pooled to prepare quality control (QC) samples, while ultrapure water was used as a blank control. Seed metabolite changes were analyzed by LC-MS/MS.

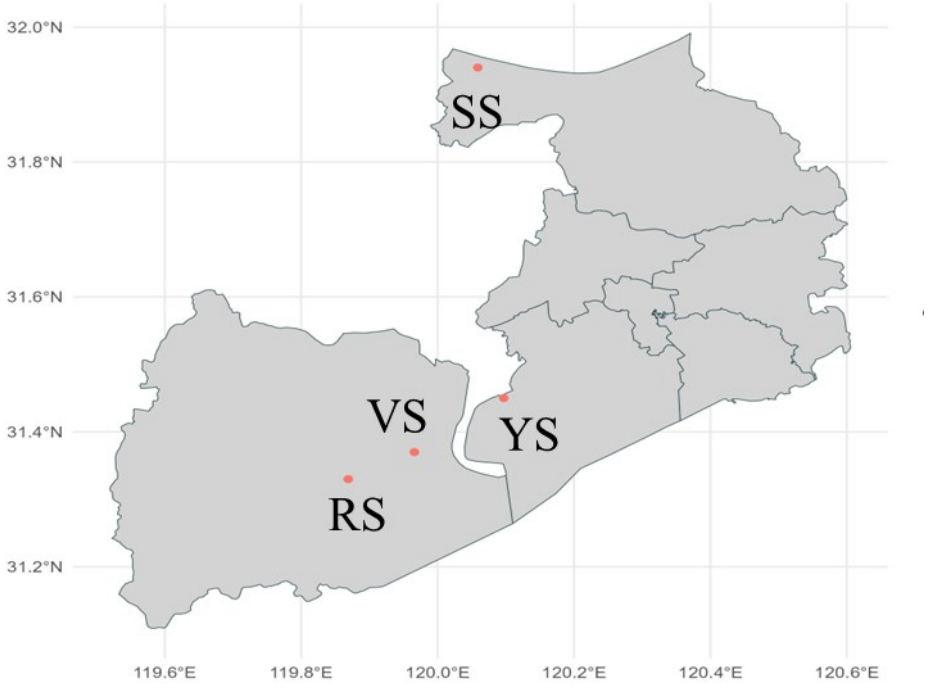

Figure S1 Soil sampling sites

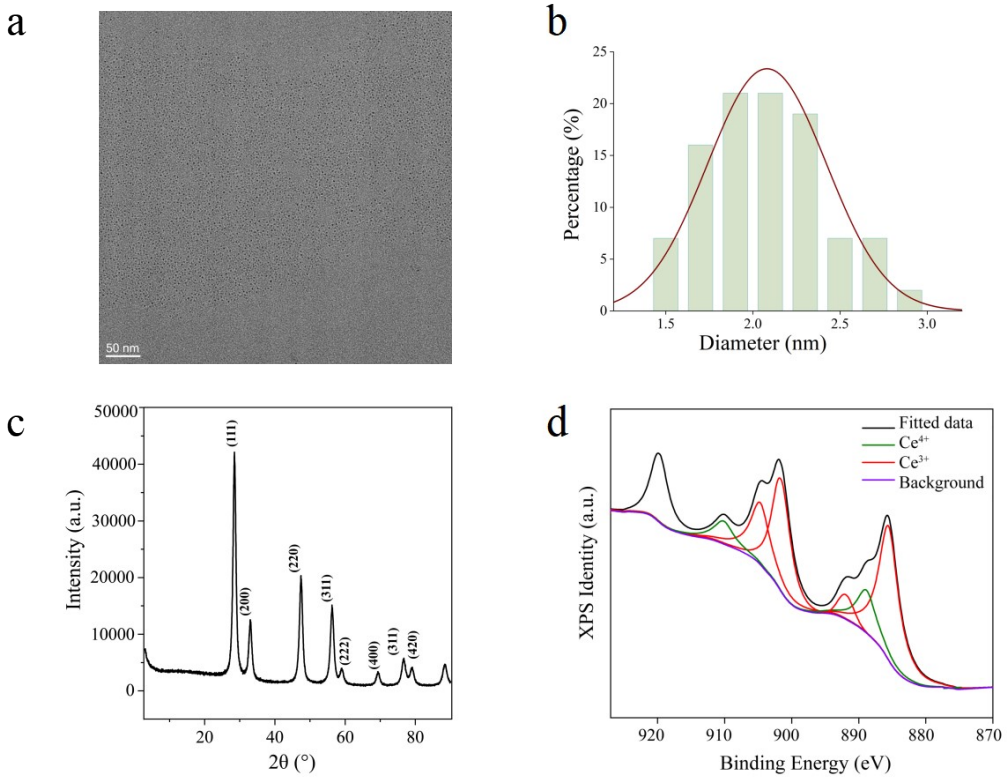

Figure S2 Characterization of CeO_2 NMs. (a) TEM image, (b) Particle size distribution, (c) XRD pattern, (d) XPS spectrum.

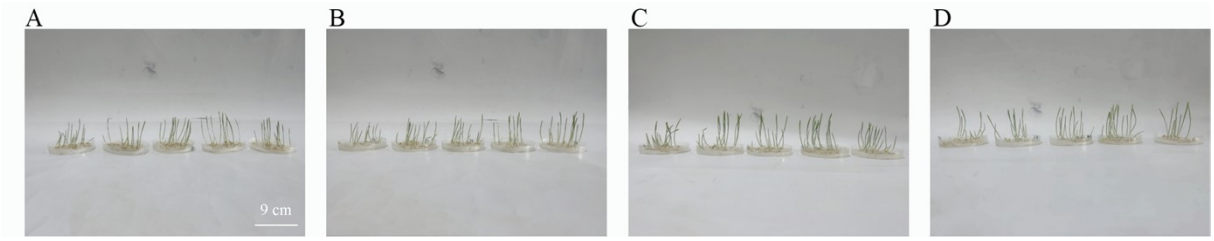

Figure S3 Effects of different concentrations of CeO_2 NMs on the growth of wheat seedlings (7 days). (A) YS, (B) VS, (C) RS, and (D) SS. From left to right, the concentrations of CeO_2 NMs are 0, 0.1, 1, 10, and 50 mg/L, respectively.

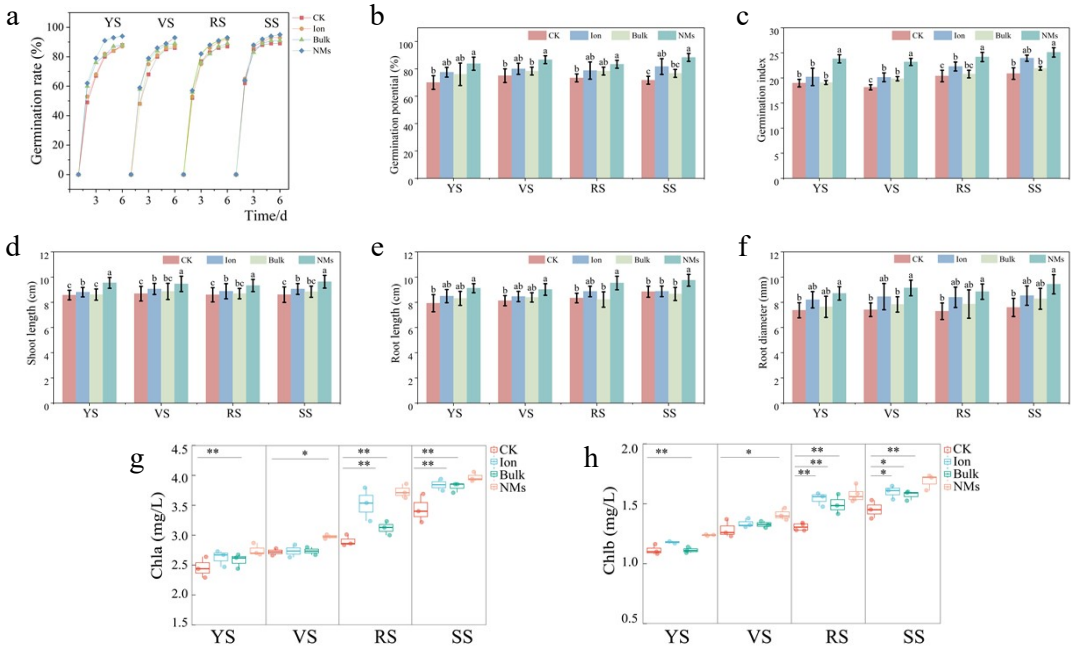

Figure S4 Effects of CeO_2 NMs, $CeCl_3$ and CeO_2 bulk treatments on wheat seed germination and seedling growth. (a) Germination rate, (b) Germination potential, (c) Germination index, (d) Shoot length, (e) Root length, (f) Root diameter, (g) Chlorophyll a, (h) Chlorophyll b. Different letters denote significant difference among different treatments ($p < 0.05$). Asterisks indicate ** $p < 0.01$; *** $p < 0.001$.

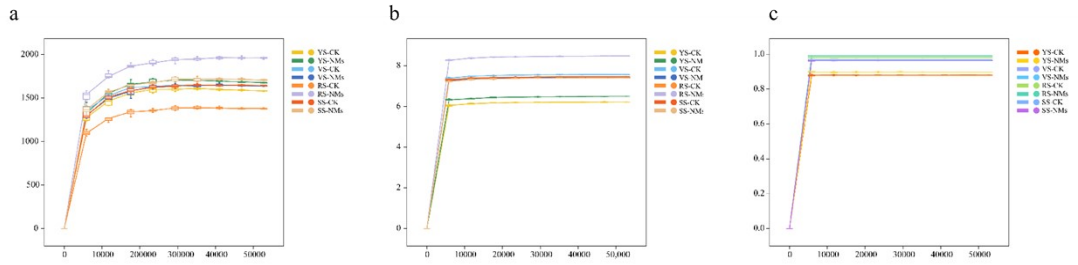

Figure S5 The coefficient curves of bacterial communities before seed germination (without seeds) after applying NMs. (a) Chao1 index; (b) Shannon index; (c) Simpson index.

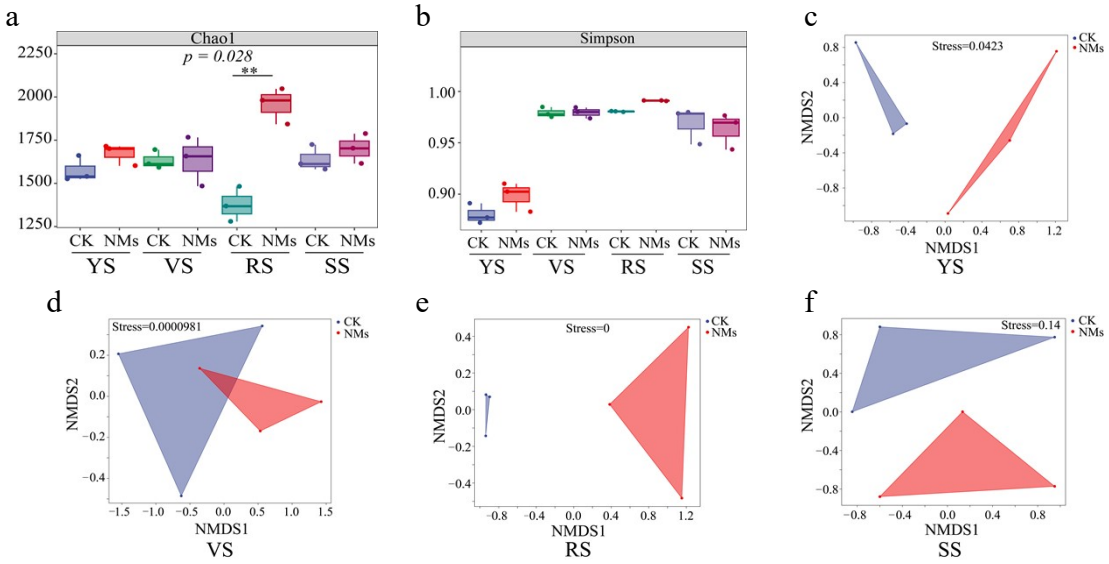

Figure S6 Differences in α and β diversity between CK and CeO_2 NMs treatments in the four soils before seed germination. (a) Chao1 index, (b) Simpson index, (c-f) Non-metric multidimensional scaling (NMDS) analysis of the four types of soil.

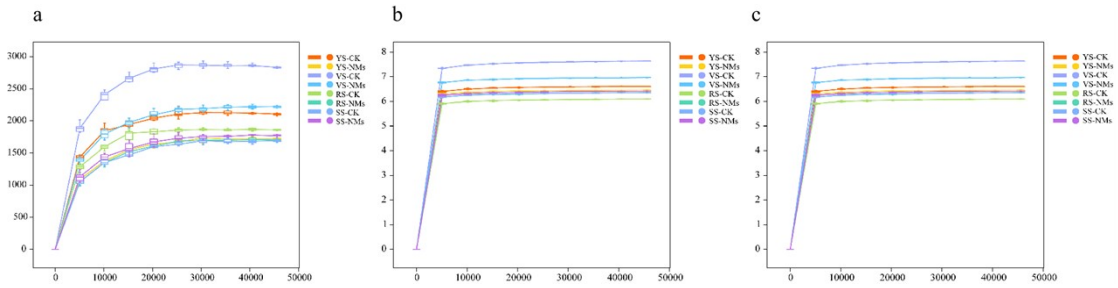

Figure S7 The coefficient curves of bacterial communities during seed germination (with seeds) after applying NMs. (A) Chao1 index; (B) Shannon index; (C) Simpson index.

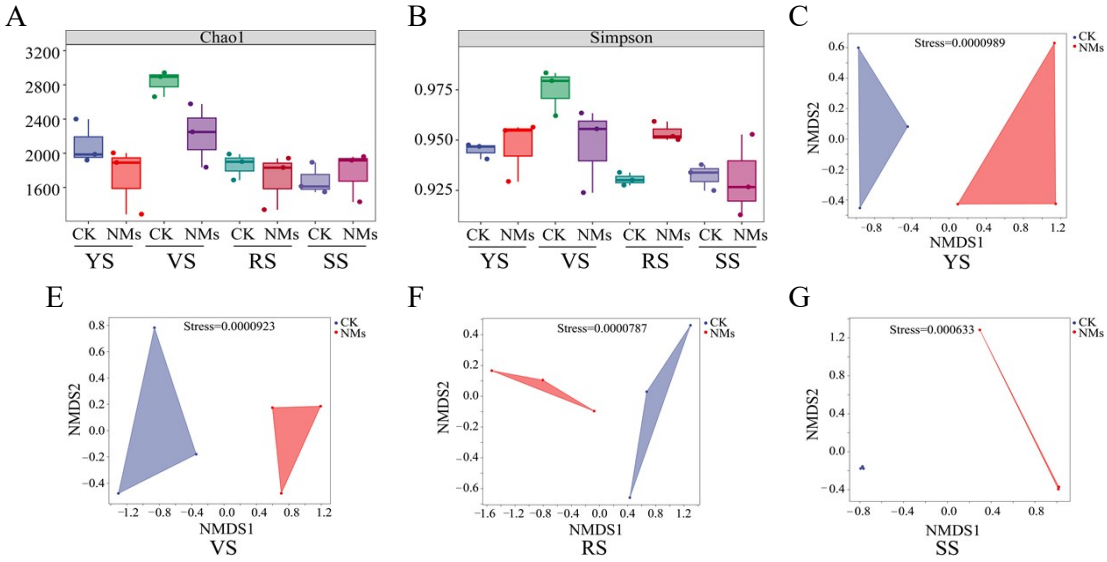

Figure S8 Differences in α and β diversity between CK and CeO_2 NMs treatments in the four soils during seed germination. (a) Chao1 index, (b) Simpson index, (c-f) Non-metric multidimensional scaling (NMDS) analysis of the four types of soil.

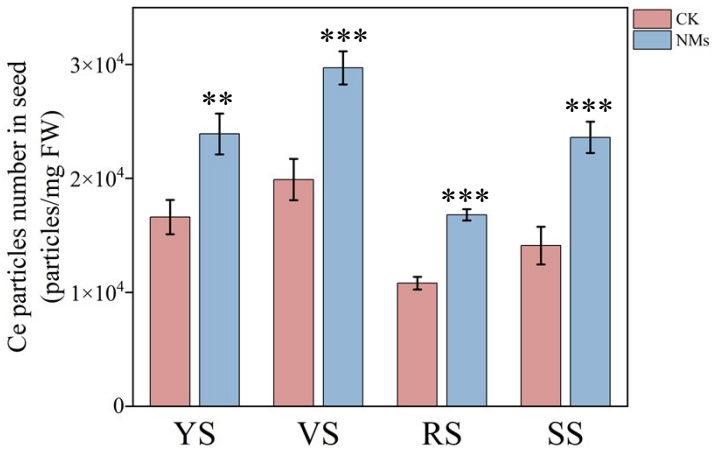

Figure S9 Number of Ce single particles in seeds during germination. Asterisks indicate ** $p < 0.01$; *** $p < 0.001$.

Table S1 Primer sequences of key genes used in this experiment

Primer name	Primer sequence (F)	Primer sequence (R)
Ta β actin	GCTGGAAGGTGCTGAGGGA	GCATCGCCGACAGGATGAG
TaPIP1;2	CGTTCCTTGCTCTCTGCTTG	GAGTAGTTATGCGTCCCATCG
TaPIP1;3	TCCTTGCTCTCCGCTTCA	CTACTGTCACATCGGTTCACT
TaPIP1;4	TTCTTCGCTCTCGGCTTCG	GAGTCAAGTCTCTCGGCATTTG
TaPIP1;5	CTTCCTTGCTCTCTGCTTCT	CTATCACATCAGTTCACCAGAC
TaPIP1;6	CTTCCTTGCTCTCCGCTTCG	CCTTGAGATCAGGGTAGGCTTT
TaPIP2	CTGCTCTACATCATCGCGCAGTG	GTGCCCTTGGAGTAGCCTGC
TaPIP3	GGTGTTCTACATCGTGATGCAGTGC	CACCAATCTCAGCCCCAAGCC
TaTIP2-3	GAGATCATCGTCACCTTCGGGCTC	GATGTTGGTGAAGTCGCCGCTG
TaNCED1	TCATCGCCGTCCACCAGGAA	TTGAGGCTCTGCCCGTCCTT
TaNCED2	ATCCACGACTTCGCCATCA	CGTCCACCCACATCATCTCC
TaCYP707A1	GCCAGGAAGCGGAACAAG	AAGAGGTGCGCCTGAGTA
TaCYP707A2	ACGTCGAGTACAGCCCATTC	TCGTCGTCGTCGTAGTTGTC
TaGA20ox1	CCGCCAGGACATGATGGATT	CGATCGACGGATGACGATGT
TaGA20ox2	AAGGTGTCGCCGATGTTGAT	ATGCGGTGCAACTACTACCC
TaGA20ox3	ACCGTGTCCTTCAACTGCTC	ATGTCACGGTACTCTTCGCC
TaGA20ox4	TCTCCTTCAGCCACAACCAC	AGCACCTCCATTATCGCCAG
β-tubulin	CATGCTATCCCTCGTCTCGACCT	CGCACTTCATGATGGAGTTGTAT
YUCCA9	GATTCTGGGCATCTCAACA	GGGACCACCTTTATTTCG
AUX1	CCGTCATTCCACAACTACC	ACATCGCGTGCATTATCT
ARF	AGCCAAAAGCAGAACTACC	AGCCATCCCAAGCACTAT
UGT	CTCACCTTTAGTGGCTTTTG	CTCACCATCGCATCTCAG
ACX1	GGGTGTTATGCACAGACTGAGC	AGACGAGCGTAAACAACAGCAT
ACX2	CGGATCCAACGATTGTCTTTAC	GTCGGGAATTGAAAAAGTCGAA

Table S2 Zeta potential and average hydrodynamic diameter of CeO_2 NMs.

NMs	Zeta potential (mV)	Hydrodynamic diameter (nm)
10 mg/L CeO_2 NMs	19.4±1.1	531.0±17.3
50 mg/L CeO_2 NMs	23.2±2.2	1101.3±69.6

Table S3 The physical and chemical properties for four types of soil.

Soil type	YS	VS	RS	SS
pH	6.91 ± 0.104 b	5.22 ± 0.261 d	5.72 ± 0.097 c	7.89 ± 0.068 a
EC	0.176 ± 0.008 b	0.079 ± 0.0009 c	0.064 ± 0.002 d	0.386 ± 0.005 a
TC	7.30 ± 1.13 b	11.60 ± 2.35 a	2.44 ± 0.21 c	13.36 ± 2.06 a
TN	0.68 ± 0.08 c	1.23 ± 0.19 a	0.52 ± 0.04 c	1.00 ± 0.14 b
OM	5.69 ± 1.87 c	15.31 ± 2.19 a	3.72 ± 0.69 c	11.03 ± 3.29 b
NH_4^+-N	19.78 ± 2.12 a	15.28 ± 4.36 b	5.89 ± 1.27 d	10.35 ± 1.36 c
NO_3^--N	4.23 ± 0.04 b	4.25 ± 0.06 b	4.22 ± 0.07 b	6.27 ± 0.92 a
AP	2.95 ± 0.32 c	29.49 ± 1.61 b	1.31 ± 0.59 c	35.65 ± 1.48 a
AK	56.78 ± 15.98 c	87.67 ± 13.74 b	46.44 ± 4.82 c	309.35 ± 11.42 a