Note: Page numbers in *italics* and **bold** refers to figures and tables respectively.

## а

abiotic stress 47, 173, 207-209 alleviation of 210 mitigation by AgNPs 174 nanosensors role in managing 15 nanotechnology applications in managing 111-118 tolerance by plants 88-89 abscisic acid (ABA) 174, 203 acid hydrolysis of cellulose fibers 270 actinomycetes, nanomaterial synthesis using 9-10 action-based nanofertilizers 83, 379 adenosine triphosphate (ATP) 117 adsorption 270-271 advanced plant disease management 339-340 Aflatoxin B1 (AFB1) 355 aggregation-induced emission active materials 283 agricultural pest and pathogen control 334 agriculture basis of 377 chitosan application in 238-239 nanotechnology evolution in agriculture field 335 NM applications in 215 soil microbial communities 136-137 agrochemical residues detection CQDs application in 291 fungicides and insecticides 293-294 pesticides and herbicides 291-293 agrochemicals, targeted delivery of 339 agroindustrial byproducts (AIB) 170 alachlor herbicide detection 293 alkali-activated cement (AAC) 264 allotropy of carbon 308 amine-functionalized GO 207 1-aminocyclopropane-1-carboxylate (ACC) 2

anionic dyes. see water-soluble hydrophilic dyes antibiotic resistance genes (ARGs) 2-3 antifungal mechanism 350 antimicrobial action of NPs 123, 123-124 antimicrobial properties of AgNPs 165-166, 178 applications as antimicrobial agents 168 effects on pathogen growth inhibition and disease suppression 167 mechanisms of action against plant pathogens 166-167 antioxidant enzymes 205-206 apoplastic pathways 171 arabidopsis and NP exposure 208 arc discharge method 6, 162, 287-288 arsenic (As) mitigation of arsenic stress 274 pollution in soil 261 ascorbate peroxidase (APX) 113, 205 aspartic-acid-coated magnetite NPs (A-MNPs) 206 Aspergillus sp. 10 assessing environmental fate and impacts 179 atom transfer radical polymerization (ATRP) 244 atomic force microscopy 244 atrazine 246 Australian Pesticides and Veterinary Medicines Authority (APVMA) 388

## b

bacteria, nanomaterial synthesis using 9 bacterial disease management, NP-based approaches to 357 bacterial pathogens 167 bactericide, NC-based pesticide 57–59 ball milling. *see* mechanical milling banana biochar (BNF) 90–91 banana bunchy top virus (BBTV) 339 Barley yellow dwarf virus (BAYDV) 350

Nanotechnology-based Sustainable Agriculture, First Edition. Edited by Pardeep Singh et al. © 2025 Wiley-VCH GmbH. Published 2025 by Wiley-VCH GmbH.

beet necrotic yellow vein virus (BNYVV) 339 biochar 265 biochar-based NCs (BNCs) 59-60 biocomposites, synthesis from 243 biofertilizers 24, 84 biofilm formation, inhibition of 352 biofortification and plant health 342 biogenic metal colloidal (BMC) solutions 205 biological method 109-110 for AgNPs synthesis 162 of HM remediation 265-267 for NMs synthesis 195 biomass accumulation influence of AgNP treatment on crop yield 176 promotion of 175 root growth promotion 175 shoot growth enhancement 176 stress tolerance improvement 176 biomolecules, AgNPs interaction with 166 biopolymers 234 -based ChNPs 351 -based NCs 61-62 bioremediation techniques 260, 262 biostimulants 211 biosurfactants 266 biosynthesized nanomaterials 117 biotic factors 47 boron-based nanofertilizers 21 bottom-up approach 7-8, 109, 286, 336. see also top-down approaches chemical vapor deposition 7 hydrothermal method 8 sol-gel method 7 spinning method 7–8 Brunauer-Emmett-Teller isotherm (BET) 244, 273

## С

cadmium (Cd) mitigation of Cd toxicity 273 pollution in soil 261-262 removal from PBNPs 273 calcium-dependent protein kinase (CDPK) 203 Canada Agricultural Products Act (CAPA) 387 Canadian Environmental Protection Act (CEPA) 387 Canadian Food Inspection Agency (CFIA) 386 carbon dots (CDs) 311-313 carbon nanodots (CNDs) 312 carbon nanofibers (CNFs) 50 carbon nanomaterials (CNMs) 4, 206 carbon nanoparticles (CNPs) 283 carbon nanotubes (CNTs) 13, 50, 116-117, 269, 307.311 CNT-based sensor for metal ion detection 315-316

carbon quantum dots (CQDs) 283-284, 312 application in agrochemical residues detection 291-294 organic contaminants and impacts on plants and environment 288-290 photocatalytic degradation of organic contaminants 294-295 properties and potential application of 284 structure of 284-285 synthesis method 285-288 carbonaceous nanoparticles 241 carbon-based nanomaterials 50, 136, 269, 305, 307-308 allotropy of carbon 308 as alternative strategy in heavy metal sensing 308-309 applications related to metal ion detection 317-320 carbon nanotubes 311 challenges associated with usage of 320 - 322conventional methods for toxic metal ions detection in soil 307 fullerenes 311 future prospects of 322-323 graphene 310 nanodiamonds 310-311 sensing mechanisms of toxic metal ions 313-317 for sensing purpose of sensing tool 308 soil contamination by toxic metal ions 305-306 types of 309 unique properties of 309 carbon-based polymer composites 50-51, 51 carbonized polymer dots (CPDs) 312 carrier-based nanomaterials 11-14 nanofertilizers 15 nanopesticides 14 nanosensors 15 stimuli-responsive nanocarriers 15, 20 carrier-free nanomaterials 20-21 macronutrient NFs 22-24 micronutrient NFs 21-22 nano-biofertilizers 24-25 cell membrane cell wall and cell membrane destruction 352-353 disruption of integrity 166 cellulose nanocrystals (CNC) 270, 350 ceramic-based NC 49 ceramic-ceramic-based NC 49 cerium oxide NPs 207 chemical ablation method 287 chemical fertilizers 1-3, 24, 77 chemical immobilization 271

chemical method biochar 265 electrokinetic method 265 of HM remediation 265 for nanomaterials synthesis 109 for NMs synthesis 195 for synthesis method of AgNPs 162 washing 265 chemical reduction method 162 chemical vapor deposition (CVD) 7 chemically bonded phosphate cement (CBPC) 264 chilling stress 113 chitin 237 chitosan 234 advantages and limitations 250 applications of 238 biological properties 236 chemical structure 234 chitosan-based NCs 62-64 chitosan-based NF 83 future perspective and research directions 250-251 herbicides removal 245-247 immobilization and removal of heavy metals 248-250 key research studies 245 mechanical properties 236 nano adsorbent for soil remediation 242-245 nanotechnology and soil remediation 239-242 organic pollution degradation 247-248 pesticide removal 247 role of functional groups 235 solubility 235 synthesis and modification 236-237 thermal properties 236 viscosity 236 chitosan beads modified with ZnO nanoparticles (CS-ZnONP) 247 chitosan nanoparticles (CSNPs) 89, 206, 238, 351 functionalization of 244-245 synthesis of 242-243, 244 chitosan nanopolymers 189 chitosan-lignosulfonate (CS-LS) nanohybrid 351 chlorophyll content, changes in 198-199 ChNPs. see chitosan nanoparticles (CSNPs) chromium (Cr) pollution in soil 262 removal from PBNPs 272-273 chromium stabilization in soil 248 CHT-NPs. see chitosan nanoparticles (CSNPs) Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) 339 composite NPs 195 consistency-based nanofertilizers 382 consistency-based NFs 84

Control of Substances Hazardous to Health (COSHH) 386 controlled-release (CR) system 49 conventional agriculture procedures 77 shortcomings of 2-3 conventional fertilizers 1, 77 conventional methods for toxic metal ions detection in soil 307 conventional remediation techniques biological methods 265-267 chemical methods 265 of HM soil pollution 264 nanotechnology-assisted HM remediation 265 physical methods 264 copper NPs (CuNPs) 58, 269-270 copper-based nanofertilizers 22 crop plant growth and development 199-201 impact on photosynthesis 198-199 NM-crop plant interaction 196-197 nutrient uptake and assimilation 201-202 physiological effects on 198 crop productivity and sustainability, adverse effects of NCs 64-66 crop resilience 215 crop resistance, NMs in enhancing 210-211 crop-pathogen systems 211 crop-specific effects of NM 210 cross-linking method 243, 244 cucumber mosaic virus (CMV) 354 curcumin-copper oxide [Cur-Cu] NPs 352 customization of NFs 90-92 dosage optimization 90-91 method of application 91-92

## d

d-block metal quantum dots 283 Deepening Ethical Engagement and Participation with Emerging Nanotechnologies (DEEPEN) 390 degree of deacetylation (DD) 235 dehydrogenases 140 demineralization 237 dendrimer 11-13, 12, 189 deoxynivalenol (DON) 355 Department for Environment, Food and Rural Affairs (DEFRA) 386 Department of Biotechnology (DBT) 389 Department of Science and Technology (DST) 390 dichlorodiphenyltrichloroethane (DDT) 3, 116 diquat 246 disability adjusted life years (DALYs) 233 disease suppression, AgNP effects on 136 dosage optimization 90-91 dose-response assessment 218

double-stranded RNA (dsRNA) 347 drought stress 111–112 fullerenol NPs and 208 mitigation 174 dynamic light scattering (DLS) 165, 195–196

## е

ecological system risks caused by NFs 96 ecotoxicology Ag-NPs, effect of 141-142 copper NPs, effect of 142-143 iron NPs, effect of 142 of NMs 216-217 of NPs 139 titanium NPs, effect of 140-141 zinc NPs, effect of 139-140 effective remediation techniques 233-234 electrochemical carbonization 287 electrochemical sensing, nanocarbon in 313 electrokinetic method 265 electron beam lithography (EBL) 5 electrostatic interactions 245 emulsification 243 emulsion solvent diffusion 243 endocytosis 171 endophytic microbes and NMs 207 energy-dispersive X-ray spectroscopy (EDX/EDS) 6, 195, 244, 273, 349 engineered nanomaterials (ENMs) 138-139, 188 engineered NPs (ENPs) 189 Engines of Creation (Drexler) 135 enhanced crop growth, AgNPs role in 178 enhanced nutrient uptake, AgNPs role in 173 Environment (Protection) Act 389 Environment, Health and Safety (EH&S) 390 environmental pollution 305 Environmental Protection Agency (EPA) 385 environmental stress 105 enzymatic activity 204-209 enzymatic method 237 enzyme-mediated synthesis 162 essential HMs 257, 263 essential metal 115 ethylenediaminetetraacetic acid (EDTA) 265 European Chemical Agency (ECHA) 387 European Commission (EC) 118-119, 387 European Food Safety Authority (EFSA) 387 evaporation-condensation method 162 exposure assessment 218 extracellular mechanism 9

## f

fabrication techniques 3, 4 bottom-up approach 7–8 top-down approaches 3–6

Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) 386 Federal Office for Agriculture (FOAG) 388 Federal Office for the Environment (FOEN) 388 Federal Office of Public Health (FOPH) 388 fermentation method 237 fertilizers 1, 187-188 next-generation delivery mechanisms for 357 fluorescence resonance energy transfer (FRET) 339 fluorescent CQDs 283 foliar application of NMs 196 foliar spray 91, 168 food processing, NPs advancements in 355-356 Food Safety and Standards Authority of India (FSSAI) 389 food security 333 Food Standard Agency (FSA) 386 Food Standards Australia New Zealand (FSANZ) 388 Fourier transform infrared (FTIR) 120, 165 Fourier transform infrared spectroscopy (FTIR) 196, 244, 273 free radical polymerization 244 fullerene 189, 311 fullerenol NPs (FNP) 112, 208 fullerol 189 functional group addition 245 fungal infections, NPs utilization for managing 361 fungal nanotechnology 335 fungal pathogens 167 fungi, green synthesis of NP using 10 fungicide 290, 293-294 NC-based pesticide 57-59 Fusarium oxysporum sp. 122

#### g

gene expression and signaling pathways 202 changes in gene expression profiles 202-203 key signaling pathways 203-204 gene expression regulation 173 genetic improvement, enhancing crop performance through 362 β-glucuronidase (GUS) 14 gold NPs (AuNPs) 189, 198-199, 201, 206, 274, 338 grafting method 244–245 graphene 189, 307, 310 graphene-based sensor for metal ion detection 314 graphene oxide (GO) 58, 121, 207 graphene quantum dots (GQDs) 292, 312. see carbon quantum dots (CQDs) green chemistry techniques 268

green fluorescent protein (GFP) 14 green synthesis of nanomaterials 8 using actinomycetes 9–10 using bacteria 9 using fungi 10 using microorganism 8–9 using plant extract 10–11 green synthesis of NPs 274–275, 336 greener nanoscience 145 growth inhibition AgNP effects on pathogen 167 of NMs 212–213

## h

Haber-Bosch process 378 harnessing nanosensors, for smart agricultural practices 362 hazard assessment 217 Hazardous and Other Wastes Rules 389 Health and Safety Executive (HSE) 386 heat shock proteins (HSPs) 114 heat stress. see thermal stress heavy metals (HMs) 59-60, 257 carbon-based nanomaterials in sensing 308-309 conventional remediation techniques of soil pollution 264-267 Cu<sup>2+</sup> decontamination from soil 248-249 effects on plants 263 immobilization and removal of 248 list of 258-259 removal 257, 260 removal of Cd(II) 249 sources and effects of pollution 260, 260-263 stabilization of chromium in soil 248 stress reduction 174 uranium (VI) sorption 249-250 herbicides 291-293 atrazine removal 246-247 diquat removal 246 NC-based pesticide 57-59 organic pollution degradation 247-248 removal in agriculture 245 hexachlorocyclohexane (HCH) 116 high-energy ball milling method 79-80 hormonal regulation of AgNPs 174 human health risks caused by NFs 96 hybrid functionalization 245 hybrid NFs 83 hydrogen bonding 245 hydroponic systems 197 hydrothermal method 8, 286 hydroxyapatite (HAP) 200, 201 hypoxia and anoxia stresses 117-118

i immobilization 264, 271 incidental NPs 189 Indian Council of Agricultural Research (ICAR) 389 Industrial Research Assistance Program (IRAP) 147-148 inner filter effect (IFE) 291 inorganic fertilizers 356 inorganic nanofertilizers 381-382 inorganic NFs 83 insecticides 290, 293-294 Insecticides Act 389 Internal Revenue Service (IRS) 147 International Air Transport Association (IATA) 93 intracellular mechanism 9 ionic gelation 242-243 iron based nanofertilizers 21-22 iron-regulated ferrous iron transporter (IRT1) 120

# j

jasmonic acid (JA) 354

## k

K-means clustering 93

## l

lactic acid fermentation 237 laser ablation method 5, 162 lead (Pb) pollution in soil 261 removal from PBNPs 273 lignin aromatic polymer 351 lipophilic NPs 196 liposomes 189 lithography 5

#### т

macronutrient nanofertilizers 22-24, 381-382 magnesium 23 nitrogen 23 phosphorus 23 potassium 24 sulfur 24 magnesium nanofertilizers 23 magnesium oxide nanoparticle (MgONPs) 349 magnesium-codoped CQDs (Mg-CQDs) 292 magnetic micro-beads 338 magnetic NPs 189 magnetic resonance imaging (MRI) 111 magnetic zeolite nanocomposites (MZNC) 355 Markov decision process 93 mask lithography 5 maskless lithography 5

maximum residual levels (MRLs) 387 mechanical milling 4 mercury (Hg) 257 pollution in soil 262 in water and sediment samples 316 mesoporous silica nanoparticles (MSNs) 13 metal ion detection by carbon-based nanomaterials 317-320 CNT-based sensor for metal ion detection 315-316 graphene-based sensor for metal ion detection 314 nano-diamond-based sensor for metal ion detection 314 other nanocarbons for metal ion detection 316 sensing mechanisms for 313 metal NPs 58, 169, 189, 198, 199, 207 metal oxide-based NPs 189 metal-based NC 49, 50 metal-based polymer composites 50 metallic nanomaterials 50 metallic nanoparticles 241 metallic NPs 136 metallic oxide nanoparticles 241 metalloids 257 methylglyoxal detoxification 173 microbes 89 microbial diversity by NPs 137 changes in community structure 138 NMs impactson microbial function and soil health 138-139 microbial remediation 266 microbial synthesis 162 microemulsion technique 162, 243 micronutrient nanofertilizers 21-22, 382 microorganism, nanomaterial synthesis using 8-9 microscopic techniques 195 micro-spectroscopy techniques 196 microwave irradiation method 286 minimum inhibitory concentration (MIC) 350 Ministry of Agriculture and Farmers Welfare, Government of India 390 Ministry of Agriculture and Rural Affairs (MARA) 388 Ministry of Environment, Forest and Climate Change (MoEFCC) 389 Notification on Manufacture, Storage, and Import of Hazardous Chemical Rules 389 Ministry of Environmental Protection (MEP) 388 mitigation arsenic stress 274 of Cd toxicity 273-274 strategies for addressing NP-related risks 363-364 mitogen-activated protein kinase (MAPK) 203 mixed nanocomposite (MNC) 56

mobile genetic elements (MGEs) 2 molluscicides 290 montmorillonite (MMT) 57 *Moringa* 113–114 multidrug-resistant (MDR) 357 multiwalled carbon nanotubes (MWCNTs) 114, 117, 189, 200, 201, 269, 311 mycotechnology 10 mycotoxins 355

#### n

nano adsorbents 240-241 benefits using 241 enhanced reactivity 241 high surface area 241 reduced secondary pollution 242 selectivity and functionalization 242 small intraparticle diffusion distance 242 versatility 242 nano bar-code 338 nanobeads 87 nano-biofertilizers (NBFs) 24-25, 84, 356 nanocarbon in electrochemical sensing 313 for metal ion detection 316 nanocarrier-loaded NFs 84 nano-chitosan-urea composite (NCUC) 57 nanocomposite-based plant fertilizers (NCPFs) 55-56 nanocomposites (NCs) 48-49 agrochemicals 47-49 application and effects of 52, 55 based fertilizer 55-57 based pesticide 57-59 based sensors 60-61 biochar-based NCs 59-60 biopolymer-based NCs 61-62 biotic and abiotic factors to crop losses 48 biotic and abiotic stress 47 carbon-based polymer composites 50-51 challenges and future of 67 chitosan-based NCs 62-64 controlled-release system 49 crop productivity and sustainability, adverse effects of 64-66 indiscriminate application of, conventional agrochemicals results 48 metal-based polymer composites 50 nanoagrochemicals 48-49 NC-based fertilizer 55-57 NC-based materials as sensors 60-61 NC-based pesticide 57-59 plant development and productivity 51-52, 52, 53-54

positive effects on plant, application of 52, 53-54, 55 types and uptake through roots and leaves 49-50, 50 nano-diamond-based sensor for metal ion detection 314 nanodiamonds (NDs) 310-311 nanoemulsions 87-88 nanoencapsulation 335 nano-enhanced fertilizers 340 nanofabrication techniques 336-337 nanofertilizers (NFs) 15, 78, 149, 356, 379 action-based nanofertilizers 379 advantages of 95-96, 381 application and benefits of 381 classification of 380 classification of 83-84 consistency-based nanofertilizers 382 contribution to sustainable agriculture 79, 88-89 customization of 90-92 disadvantages of 381 ethical, regulatory and safety issues 93-95 ethical and safety concerns of 390-391 future perspective 97 improving water and nutrient retention in soil 87-88 increased nutrition uptake by plants 87 integration with precision agriculture 92-93 limitation of 96 macronutrient 22-24 mechanism of nutrient release and uptake by plants 85-87, 86 method of application 148-149 micronutrient 21-22 mode of action 84 nanoformulations 14, 16-20 nanostructured particles 78 and nutrient delivery 215 nutrient-based nanofertilizers 381-382 significance in current agriculture 80-82, 81-82 significance on environment 149 types and synthesis methods 78-80 nanoherbicides 378-379 nanolithography 5 nanomaterial synthesis. see green synthesis nanomaterial-based chemicals for sustainable agriculture nanofertilizers 379-382 regulations and safety measures 385-390 risk assessment 382-383 risk management 384-385 uncertainties 383-384 nanomaterials (NMs) 119, 187, 355. see plant-based nanomaterials (PBNPs)

agricultural shortcomings 2-3 applications in agriculture 215 approaches to minimize negative impacts 145-146, 146 assessment and monitoring 143 case studies and experimental findings 209 categories of signaling pathways 209 challenges of 25-26 characterization of 109–111 as controlled delivery system 11-25 ecotoxicology of 216-217 fabrication techniques for 3-8 fertilizer 1-2 future 25-26, 214 green synthesis of 8-11 impacts microbial function and soil health 138-139 long-term effects on soil ecosystem services 143-144 methods of synthesis 195 mitigation strategies and future directions 145-146 molecular and biochemical responses 202-209 nanofertilizers 149 negative effects 211-214 NM-crop plant interaction 196-197 physiological effects on crop plants 198-202 positive effects 209-211 potential risks and benefits 144-145 practical applications 214, 220 regulatory and policy considerations 147-148 research and knowledge gaps 148-149 risk assessment and management 217-218 sensing mechanisms of toxic metal ions by 313-317 soil microbial communities, role in agriculture 136-137 studying physiological effects of crop plants 188 synthesis 4, 109-110 techniques for characterization 195-196 types and agricultural applications 136 nanoparticles (NPs) 2, 78-80, 106, 187, 239, 260, 283, 333, 336, 347-348 advancements in food processing and packaging technologies 355-356 antimicrobial action of 123, 123-124 changes in microbial community structure 138 emerging strategies for mitigating plant diseases via 354 enhancing crop performance through genetic improvement 362 harnessing nanosensors for smart agricultural practices 362 microbial diversity, effect of 137-139 mitigation of stress 108

nanoparticles (NPs) (Cont.) mitigation strategies for addressing NP-related risks 363-364 nano-biofertilizers 356 next-generation delivery mechanisms for fertilizers and nutrients 357 NP-based approaches to bacterial disease management 357 NP-based platforms for effective insecticide application 361-362 phytoregulators 119-120 plant disease management through 351-354 preserving soil integrity and functionality 120-121 role in disease resistance 340-341 role in managing viral infections 357, 358-361 role in soil remediation 267 stress tolerance as key to optimizing crop productivity 356 synthesis 187, 336-337 techniques to better seed germination and plant development 355 types of 189-190, 190-194, 195 used in plant disease management 348-351, 349 utilization for managing fungal infections 361 nanopathology 334, 337 advanced plant disease management 339-340 biofortification and plant health 342 challenges 342 early detection and diagnosis 337-339 plants to fight with pathogens and growth and development 334 soil and water treatment 340-342 targeted delivery of agrochemicals 339 nanopesticides 14, 378 and crop protection 215 ethical and safety concerns of 390-391 utilizing in plant defense 121-122 nano-phytoremediation 271 nanopolymers 189 nanopore sequencing 338-339 nano-priming 91-92, 210, 211 nano-remediation 260 nanoscale additive fertilizers 83 coating fertilizers 83 fertilizers 83 materials 336 nanoscale zero-valent iron (nZVI) 115, 202, 269 nanosensing methods 348 nanosensors 15, 337-338 plant-system-interrogating nanosensors 60-61, 337-338 and precision agriculture 215

nanosheets 336 nanotechnology 135-136, 159, 187-188, 239-242, 267, 333-334 applications of 336-337 aspects of 336 characterization of nanomaterials 109-111 environmental challenges 105 environmental implications 118-119 evolution in agriculture field 335 future perspectives 124-125 key characteristics 335 in managing abiotic stress 111-116 nanotechnology-assisted HM remediation 265 pesticides 106-107 sustainable agricultural practices 105-108 synthesis of nanomaterials 109-110 Nanotechnology Task Force 118 nanotechnology-based agricultural products regulations in Australia 388 in Canada 386-387 in China 388-389 in Europe 387-388 in India 389-390 in Russia 388 in South Korea 389 in Switzerland 388 in United Kingdom 386 in United States 385-386 nanotoxicology 390 nanotubes 336 National Centre for Nanoscience and Technology (NCNST) 388 National Nano-Safety Strategic Plan 389 National Nanotechnology Initiative (NNI) 147 National Research Council (NRC) 148 natural NPs 189 negative oxidative stress responses of NM 212 nematicides 290 neural network algorithms 92 neural regeneration process 238 New Substances Notification Regulations (NSNR) 387 next-generation delivery mechanisms for fertilizers and nutrients 357 nitrogen nanofertilizers 23 nitrogen-doped carbon dots (N-CDs) 204 nitrogen-doped CQDs (N-CQDs) 293 nitrous oxide 77 nonessential HMs 257 non-essential metals 115 non-polymer NC 49, 50 nutrient(s) cycling process 25, 121, 136, 231 next-generation delivery mechanisms for 357 nutrient-based nanofertilizers 381-382

nutrient-based NFs 83-84 uptake and assimilation 201-202 nutrient uptake and transport enhancement by AgNPs 170 direct uptake by roots 171 effects on nutrient availability 172 formation of new pores 172 influence of Ag<sup>+</sup> ions 172 influence on cellular mechanisms 172 mechanisms of 171-172 oxidative stress and defense mechanisms 172 plant nutrient utilization efficiency 172-173 role in improving nutrient absorption by crop plants 171 soil's nutrient availability 172 translocation through xylem 171 nutrient use efficiency (NUE) 47, 55, 56, 87, 90

#### 0

oil spill remediation 248 olive knot disease 350 onion-like carbon (OLC) 310 Operational Taxonomic Units (OTUs) 141 optimizing application methods 179 ordinary Portland cement (OPC) 264 organic contaminants dyes 289 and impacts on plants and environment 288 pesticides and insecticides 290 photocatalytic degradation of 294-295 polycyclic aromatic hydrocarbons 289 organic fluorophores 283 organic pollutants (OPs) stress 116-117 organic pollution degradation 247-248 organochlorine pesticides 116 Orphan Drug Tax credit 147 oxidation 271 oxidative stress 207

## р

packaging technologies, NPs advancements in and 355–356 palladium NPs (PdNPs) 117 papaya ringspot virus (PRSV) 354 Patent Box 147 permethrin 247 peroxidase (POD) 113 pesticide 3, 290 CQDs application in detection of 291–293 removal 247 phosphate-solubilizing microbes 266 phosphorus nanofertilizers 23 photocatalytic degradation of organic contaminants 294–295 photosynthesis

enhanced photosynthetic efficiency 175 impact on stomatal conductance 175 improved chlorophyll content 175 increased nutrient uptake 175 NPs impact on 198 promotion of 175 physical methods for AgNPs synthesis 162 of HM remediation 264 phytohormones 354 phytonanotechnology 268 phytoregulators 119-120 phytoremediation 266, 271 phytotoxicity of NMs 211-212 plant biomolecules 268 plant development and productivity of NCs 52-64, 52, 53-54, 55 plant disease management cell wall and cell membrane destruction 352-353 emerging strategies for mitigating plant diseases via NPs 354-362 inhibition of biofilm formation 352 interaction with biomolecules 353-354 NP types used in 348-351 through NPs 351 plant extracts 162 nanomaterial synthesis using 10-11 plant growth-promoting bacteria (PGPB) 2 plant growth-promoting rhizobacteria (PGPR) 24, 136 plant health, biofortification and 342 plant-based nanomaterials (PBNPs) 260, 268 applications in HM remediation 271, 272 carbon-based nanomaterials 269 copper NPs 269-270 Cr removal 272-273 limitations of 274 mechanism of action 270-271 mitigating arsenic stress 274 mitigation of Cd toxicity 273-274 Pb removal 273 polymer NPs 270 quantum dots 270 removal of Cr, Cd, and Pb 273 synthesis of 268 types of 269 zero-valent iron NPs 269 plant-growth-promoting rhizobacteria (PGPR) 271 poly(amidoamine) (PAMAM) dendrimers 12, 12 polybrominated diphenyl ethers (PBDEs) 116 polychlorinated biphenyls (PCBs) 117 polychlorinated dichlorodiphenyltrichloroethane 116

polycyclic aromatic hydrocarbons (PAHs) 116, 289 polyethylene glycol (PEG) 189 polymer NPs 270 polymer-based NC 49, 50 polymer-coated pesticides 14 polymeric nanoparticles (PNPs) 108, 342.350 polyol process 162 polyvinyl pyrrolidone (PVP) 189 post-harvest technologies 210 postharvest treatments, AgNPs use in 168 potassium nanofertilizers 24 potato virus Y (PVY) 354 precision agriculture, nanosensors and 215 precision farming 92 Priostar® dendrimers 12 Pseudomonas sp. 2-3 Public Health Agency of Canada (PHAC) 386 pyrolysis method 286-287

## q

quantitative structure-activity relationship
(QSAR) 92-93
quantum dots (QDs) 136, 189-190, 270, 339
quantum effects 335
quantum yield (QY) 286

#### r

Ralstonia solanacearum sp. 123 reactive oxygen species (ROS) 106, 165, 166, 189, 263, 350 generation of 166 management 173 reduction method of PBNPs 271 reinforcement learning 93 reverse micellization process 243 rhamnolipids 266 rhizobium-plant symbiotic relationship 263 risk assessment and management 217 dose-response assessment 218 exposure assessment 218 hazard assessment 217 management in nanofertilizers 384-385 preliminary activity in risk ranking 217 risk characterization 218 rodenticides 290 Russian Corporation of Nanotechnologies (RUSNANO) 388

#### S

salicylic acid (SA) 354 salinity stress. *see* salt stress salt stress 112-113 alleviation 174 scanning electron microscopy (SEM) 165, 244, 273, 349 Scientific Research and Experimental Development (SR&ED) 148 seed germination 199, 211 seed nanopriming 91-92 seed treatment 168-169 AgNP effects on germination rates and seedling vigor 169-170 AgNP influence on seedling establishment and early growth stages 170 optimization of AgNPs' application methods 170 selected area electron diffraction (SAED) 8 selenium NPs (Se NPs) 120 and temperature stress 208 sensing mechanisms of toxic metal ions employed for metal ion detection 313-316 factors influencing sensitivity 316-317 nanocarbon in electrochemical sensing 313 by nanomaterials 313 signal transduction, AgNPs inhibition of 166 silica nanoparticles (SNPs) 88 silicon NPs (SiNP) 206 silicon-based nanofertilizers 22 silicon-based nanoparticles 241 silver nanoparticles (AgNPs) 58, 112, 383 antimicrobial properties of 165-168 application of 169 characterization techniques 163-165, 164 effects on root architecture, root surface area and nutrient uptake 177 factors influencing synthesis process and NP properties 163 interactions between AgNPs and soil components affecting plant growth 177-178 methods for synthesizing 161-162 nanotechnology 159 nutrient uptake and transport enhancement 170-173 promotion of photosynthesis and biomass accumulation 175-176 promotion of root growth and development 176-177 root development and soil interaction 176-177 seed treatment with 168-170 stress tolerance improvement 173-174 sustainable agriculture applications 178-180 sustainable farming 160–161 sustainable practices 180 synthesis and characterization 161 silver precursor, concentration of 163

single-walled carbon nanohorns (SWCNHs) 189 single-walled carbon nanotubes (SWCNT) 61, 189, 198, 269, 311 Small Business Innovation Research (SBIR) 147 S-nitrosoglutathione (GSNO) 63 sodium tripolyphosphate (STPP) 242 soil amendments 168 health 257 sources and effects of HM pollution in 260 - 263treatment 91-92 soil contamination 115 by toxic metal ions 305-306 soil microbial community by NMs 136, 139 composition and functions 136-137 ecotoxicology of NPs 139-143 soil pollution 231-232 primary causes of 232-233 soil remediation 231-233, 239-242 chitosan nano adsorbent for 242 functionalization of chitosan nanoparticles 244-245 NPs role in 267 PBNPs for 268-274 primary causes of soil pollution 232-233 synthesis of chitosan nanoparticles 242-243, 244 sol-gel method 7 solidification 264 spectroscopic techniques 195 spinning disc reactor (SDR) 7-8 spinning method 7-8 sputtering method 6 stabilizing agents 163 Standardization Administration of China (SAC) 388 State Food and Drug Administration (SFDA) 388 stimuli-responsive nanocarriers 15, 20 stress mitigation 215 stress tolerance as key to optimizing crop productivity 356 stress tolerance improvement by AgNPs mechanisms of enhancement 173-174 mitigation of abiotic stresses 174 sulfur nanofertilizers 24 superoxide dismutase (SOD) 54, 202-203 and catalase activity 205 superparamagnetic iron oxide NPs (SPIONs) 198 supervised learning 92-93 surface plasmon resonance (SPR) 164 surface-enhanced Raman scattering (SERS) 61 sustainable agriculture applications of AgNPs 178-180 biotic and abiotic stress tolerance by plants 88-89

challenges 179 contribution by NFs 88 enhanced nutrient retention capacity increase microbial activity 89 integrating into agricultural practices 178 lesser environmental pollution 89 potential benefits 178 role of nanomaterials in 383 safe and responsible use in crop production 179-180 sustainable agroecosystem 56-57 sustainable development goals (SDGs) 49 symbiotic relationships 136 symplastic pathways 171 symplastic transport system 197 synergistic relationship with beneficial microorganisms 208 synthesis method of CQDs 285, 288 arc discharge method 287-288 chemical ablation method 287 electrochemical carbonization 287 hydrothermal method 286 microwave irradiation method 286 pyrolysis method 286-287 systemic acquired resistance (SAR) 203

## t

targeted delivery of agrochemicals 339 Technology Strategy Board (TSB) 147 temperature stress, Se-NPs and 208 Tephrosia apollinea sp. 111 thermal decomposition method 5-6 thermal desorption method 264 thermal stress 113-114 thiobarbituric acid reactive substances (TBARS) 205 tin-nanoparticle (Sn NP) 207 tissue engineering, chitosan in 238 titanium dioxide NPs (TiO2-NPs) 113-114 titanium dioxide-based nanofertilizers 22 tobacco mosaic virus (TMV) 167, 354 tollens' method 162 top-down approaches 3-6, 79-80, 110, 286, 336. see also bottom-up approach arc-discharge method 6 laser ablation technique 5 mechanical milling 4 nanolithography 5 sputtering method 6 thermal decomposition method 5-6 toxic gases 305 toxic metal ions conventional methods for detection 307 sensing mechanisms of 313-317 soil contamination by 305-306

toxic metal stress 115-116 Toxic Substances Control Act (TSCA) 385 traditional fertilizers 23 vs. NFs 95-96 transcription factors (TFs) 203 in ZnO-NP Response 204 transmission electron microscopy (TEM) 6, 164, 195, **244**, 273, 350 Treaty of the Functioning of the European Union (TFEU) 387 trichloroethane (TCE) 117 degradation of 247 Trichoderma 336, 336 tripolyphosphate (TPP) 242 tris-(chloroisopropyl)-phosphate (TCPP) 117 tunneling formation in roots 212 turmeric oil nanoemulsions (TNE) 170

## и

UK Expert Committee on Pesticides (ECP) 386 ultraviolet-visible (UV-vis) spectroscopy **244** United States Food and Drug Administration (FDA) 118 unsupervised learning 93 up-converting NPs (UCNPs) 362

#### V

viral infections, NPs role in managing 357, 358–361 viral pathogens 167

#### W

wastewater treatment, chitosan in 238–239 water-soluble hydrophilic dyes 289 Work Health and Safety (WHS) 388 World Health Organization (WHO) 388

#### Х

X-ray diffraction (XRD) 6, 165, 195-196, 244, 273

#### Ζ

zero-valent iron NPs 269 zeta potentials of AgNPs 165 analysis **244** of NPs 197 zinc (Zn) for living organisms growth and development 21 pollution in soil 262–263 zinc oxide nanoparticles (ZnO-NP) 113, 117 improving soil fertility 189 and salinity stress 208 on soil microbial community 139–140 transcription factors in 204