Electronic Supporting Information

Ingestion and Insecticidal Effects of Cetylpyridinium Chloride Functionalized Carbon Nanotubes on Spodoptera litura: Oxidative Stress, Metabolic Disruptions, and Reproductive Toxicity

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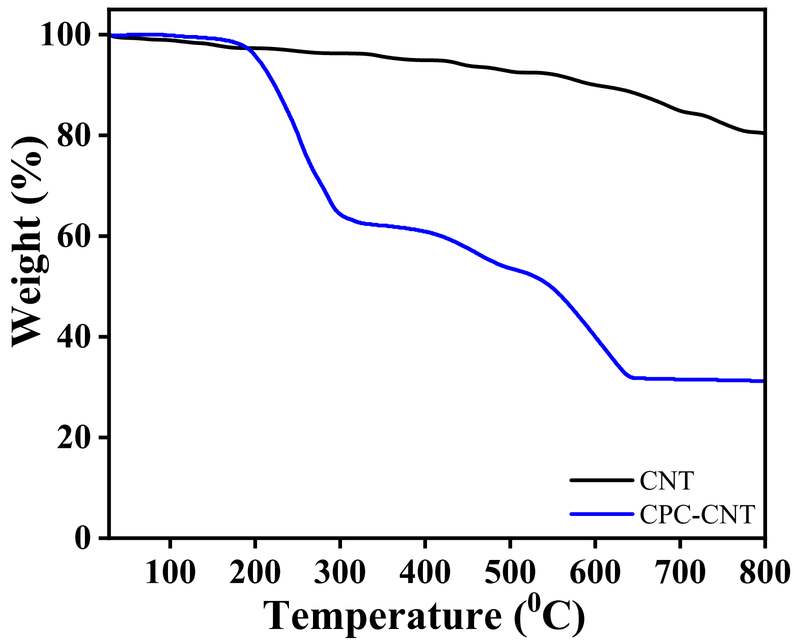

Figure S1. TGA analysis of CNT and CPC-CNT.

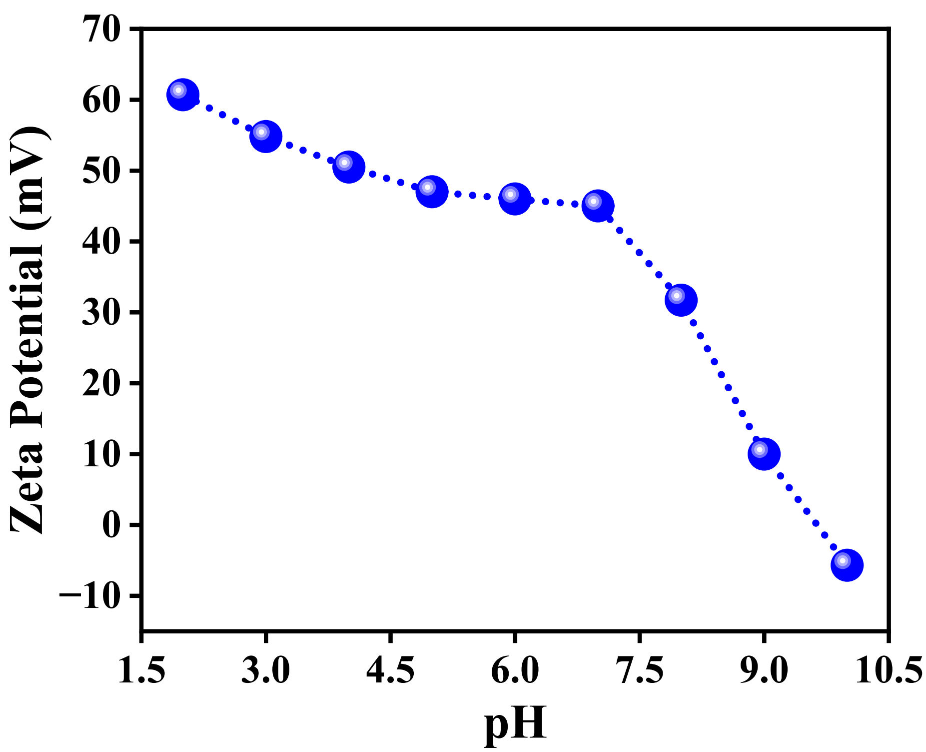

Figure S2. pH-Dependent Zeta Potential of CPC-CNT

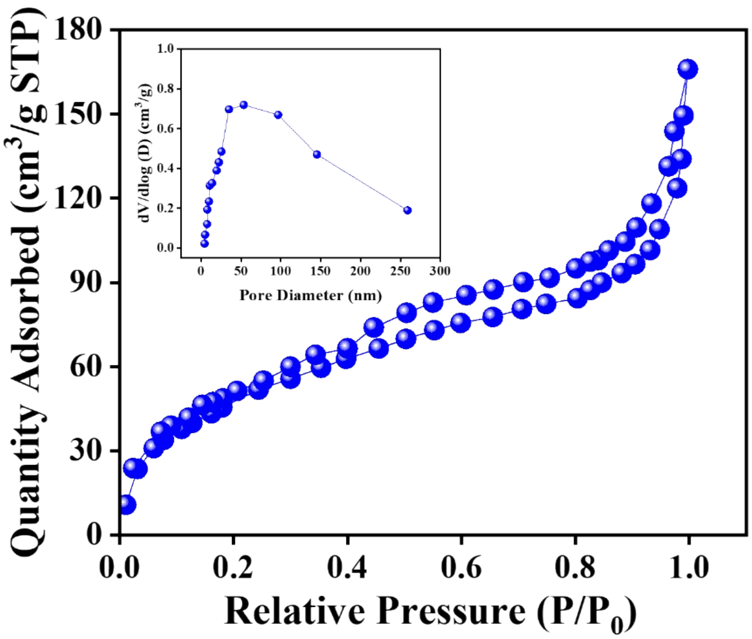

Figure S3. BET specific surface area and inset pore diameter distribution for CNT-CPC

Table S1. Comparative Overview of Nanopesticide Systems Targeting *Spodoptera litura*: Physicochemical Characteristics, Biological Effects, and Environmental Considerations

Nanopesticide Type	Source Material	Average Size (nm)	Target Organism	LC50 (g/L)	Max Mortality (%)	Effect on Development and Physiology	Environmental Considerations	Reference
Chitosan-Selenium Nanocomposite (Ch-SeNPs)	Mycosynthesized using Penicillium griseofulvum (fungal filtrate)	67.41	Spodoptera littoralis	Low LC50 (exact value not specified)	Higher than SeNPs and fungal spores	Strong larvicidal and pupicidal activity; cytotoxic ultrastructural impact; safe to honeybe	Eco-friendly biosynthesis; safe for non-target organisms (e.g., honeybees)	[1]

						es		
Selenium Nanoparticles (SeNPs)	Mycosynthesized using Penicillium griseofulvum (fungal filtrate)	91.25	Spodoptera littoralis	Low LC50 (exact value not specified)	High mortality, lower than Ch-SeNPs	Significant insecticidal activity and ultrastructural disruption in larvae	Eco-friendly biosynthesis; cost-effective; safe for pollinators	[1]
Silver Nanoparticles (AgNPs)	Chemically synthesized AgNPs	50–60	Spodoptera littoralis	Not applicable (nonlethal)	Not applicable	Reduced larval and pupal weight; increased plasmatocyte count; no change in nutrient levels	Studied at nonlethal dose; possible immune modulation; lower metabolic interference	[2]
Zinc Oxide Nanoparticles (ZnONPs)	Chemically synthesized ZnONPs	10–30	Spodoptera littoralis	Not applicable (nonlethal)	Not applicable	Extended larval period; reduced weight; decreased protein, lipid, carbohydrate levels; increased hemocyte counts; enhanced amylase, G6PD, lipase, catalase, and SOD	Nonlethal dose showed significant effects on development, metabolism, and immunity	[2]

						activities		
Hydrophobic Silica Nanoparticles (TSiNP HPHO)	Tetraethyl orthosilicate (TEOS)	Not specified (very small)	Spodoptera littoralis	10.048	100%	High impact on protein, chitinase, phenol oxidase; reduced protease, amylase	Low-cost, eco-friendly	[3]
Silica Nanoparticles from Sodium Silicate (SSiNP HPHI)	Sodium silicate	Not specified (medium)	Spodoptera littoralis	10.076	100%	Same as above	Eco-friendly; low-cost from industrial byproducts	[3]
Hydrophilic Silica Nanoparticles from TEOS (TSiNP HPHI)	Tetraethyl orthosilicate (TEOS)	Not specified (big)	Spodoptera littoralis	10.401	100%	Same as above	Biocompatible, safe; expensive precursor	[3]
Microsilica from Sand (TSi)	Sand (Top-down method)	175,000 (µm size)	Spodoptera littoralis	40.299	70%	Mild effects	Low impact; low efficacy	[3]
Tungsten Oxide (WRT)	WO_3 nanomaterial	Not specified	Spodoptera littoralis	No toxicity alone	No mortality alone	No toxic effect alone; combined increased developmental delay	Low toxicity but no standalone pesticidal effect	[4]
Magnetic Nanoparticles (MNPs)	Fe_3O_4-based magnetic nanoparticles	Not specified	Spodoptera littoralis	No toxicity alone	No mortality alone	Antagonistic in mixture; increased malform	Safe alone; activity depends on	[4]

						ations	combination	
Cu-Doped MNPs (MNP-Cu)	Fe_3O_4 doped with Cu	Not specified	Spodoptera littoralis	No toxicity alone	No mortality alone	Induced enzyme activity (GST, α-esterase); repellent	Safe alone; combination causes stress and immune modulation	[4]
Cyromazine + MNP-Cu (500 mg/L)	Synthetic + Cu-doped magnetic nanomaterials	Not specified	Spodoptera littoralis	Not specified (repellency and enzyme effects)	No adult emergence at 500 mg/L	Max repellency (57.6%); strong immune response via Q-PCR	Promising for reduced chemical pesticide use; mixture efficiency	[4]
Cyromazine + WRT (500 mg/L)	Synthetic + WO_3 nanomaterial	Not specified	Spodoptera littoralis	Not specified	27.3% adult emergence	Some adult emergence and moderate developmental delay	Moderate impact with adult emergence; less effective than MNP-Cu	[4]
Cu-Doped Zinc Oxide Nanoparticles (Cu-ZnONPs)	ZnO nanoparticles doped with copper (Cu) using wet chemical synthesis	Not explicitly stated; characterized via SEM and TEM	Spodoptera littoralis	Not specified; dose in % (1–5%)	95% population reduction at 5% Cu-ZnONPs after 16 days	Significant pest population reduction; strong dose-dependent toxicity; highest efficacy at 5% concentration	Eco-friendly and cost-effective; potential to reduce use of conventional insecticides and related	[5]

							risks	
Iron Nanoparticles (FeNPs)	Trigonella foenum-graecum leaf extract	Not specified (green synthesized, characterized)	S. litura, H. armigera	Not specified individually	Approx. 70–80% at 72 h	Strong antifeedant activity (up to 90–95%); suppressed detox enzymes (CarE, GST, P450); altered esterase banding	Green synthesis, plant-derived, eco-friendly	[6]
FeNPs + Fenvalerate (Fen)	FeNPs from fenugreek + synthetic pyrethroid (Fenvalerate)	Not applicable (mixture)	S. litura, H. armigera	130.31 mg/L (S. litura), 89.32 mg/L (H. armigera)	92.83 % (S. litura), 91.41 % (H. armigera) at 72 h	Synergistic toxicity; reduced detoxification enzyme activity; enhanced antifeedant response; resistance management potential	Combines lower dose synthetic pesticide with plant-based nanomaterial for reduced environmental risk	[6]
Silver Nanoparticles (AgNPs)	Green synthesis using Leonotis nepetifolia leaf extract	Not explicitly mentioned; characterized via SEM, TEM, DLS	Spodoptera litura, Helicoverpa armigera, Aedes aegypti, Culex quinquefasciatus	47.44 ppm (Aedes aegypti), 35.48 ppm (Culex quinquefasciatus)	Larval mortality: 78.49 % (S. litura), 72.70 % (H. armigera); Pupal mortali	Antifeedant activity: 78.77% (S. litura), 82.16% (H. armigera); Histological	Eco-friendly biosynthesis; high efficacy; potential to reduce chemical insecticide use;	[7]

					ty: 84.66 % (S. litura), 77.44 % (H. armigera)	damage to epithelial and goblet cells in larval midgut	suitable for agricultural and public health applications	
CSNp-BV (Chitosan NPs with Beauvericin)	Chitosan + Beauvericin (from Beauveria bassiana)	160–230	Spodoptera litura	Not specified, dose-dependent response observed	100% (early instars)	Reduced pupal and adult emergence, dose-dependent mortality in all larval stages	Biocompatible, controlled release, environmentally friendly formulation	[8]
CdS	Cadmium acetate & thiourea via CTAB-based method	60	Spodoptera litura	0.50884	93.79	Disruption of midgut epithelial cells, stiffening, oozing of body contents, premature moulting	Toxicity due to cadmium, possible ecological impact	[9]
Nano-Ag	Acid leaching tail solution and hydrazinium sulphate reduction	<90	Spodoptera litura	1.40314	56.89	Disruption of digestive system, oozing of gut content, cell damage	Toxic to aquatic systems, can cause chromosomal aberrations	[9]
Nano-TiO_2	Anatase with amines and NaOH	>50	Spodoptera litura	0.79110	73.79	Midgut rupture, larval swelling, discharge of	Toxicity depends on particle size and exposure	[9]

						contents, stiffened body	; less data available	
Selenium Nanoparticles (SeNPs)	Mycosynthesized using Trichoderma sp. culture filtrate	40–100	Spodoptera litura	39.739 ppm	Significant larval mortality at 48 h (LC90 = 142.839 ppm)	Strong larvicidal and antifeedant activity; histopathological damage; spherical crystalline SeNPs confirmed	Biogenic synthesis; fungal-mediated; potentially eco-friendly alternative to chemical insecticides	[10]
Fe0 Nanoparticles (Fe0NPs) from Beauveria brongniartii	Mycosynthesized using Beauveria brongniartii conidia	410–800 nm (0.41–0.80 µm)	Spodoptera litura	59 ppm (7 days post-treatment)	Not stated directly; increased mortality with dose and time	Reductions in feeding, growth rate, enzyme activity (GST, antioxidants); altered nutrient utilization	Fungus-mediated biosynthesis; supports eco-friendly pest control	[11]
Silver Nitrate Nanoparticles (AgNPs)	Cymbopogon citratus extract with $AgNO_3$	Not specified in summary	Spodoptera litura	Not mentioned	98% (AgNPs with C. citratus, ethanol-based)	Prolonged larval toxicity; high mortality at 72 h post-exposure	Eco-friendly biosynthesis, ethanol as non-toxic dispersant	[12]
Zinc Oxide Nanoparticles (ZnONPs)	Various plant extracts with ZnO	Not specified in summary	Spodoptera litura	Not mentioned	90% (ZnONPs with ethanol)	Larval mortality; ethanol improves dispersion and	Sustainable alternative to chemical insectici	[12]

						toxicity	des	
Copper Nanoparticles (CuNPs)	Copper salt precursor	N/A	Spodoptera litura	N/A	74.44 (leaf dip), 68.89 (larval dip)	Dose-dependent larval mortality observed; effective by both leaf and larval dip methods	Potential eco-friendly alternative to synthetic insecticides	[13]
CPC-functionalized Carbon Nanotubes (CPC-CNTs)	Carbon nanotubes functionalized with cetylpyridinium chloride (CPC)	~30–50	Spodoptera litura	~0.68% (estimated)	42.20% at 0.6% concentration	↑ MDA (oxidative stress), ↓ SOD/CAT, ↓ AChE (neurotoxicity), ↓ fecundity, ↓ fertility, ↓ adult emergence	Potential concern due to CNT persistence; CPC is a cationic surfactant—eco-safe handling required	This study

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