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Supplementary Information

An insight into the role of carbon dots in the agriculture System: a Review

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Table S1: Green synthesis of CDs from various plant precursors.

Precursor plant	**Synthetic method**	**Reaction conditions**	**Solvent/ chemicals used**	**Features of synthesized CDs**	**Optical property (emissive color) λex/λem (nm)**	**Quantum yield**	**Applications**	**Ref.**
Moringa oleifera	Hydrothermal	200 °C, 10 h	Water	N-CDs, 2.6 nm, monodisperse, amorphous	Blue 350/445	43.4 %	Sensing, antifungal, and plant growth enhancers	[01]
Date kernel	Hydrothermal	200 ℃, 8 h	Water	2.5 nm, uniformly dispersed, amorphous	Blue 340/430	12.50%	Sensing and cellular imaging	[02]
Lemon peel	Hydrothermal	200 ℃, 12 h	Water	N-CDs, 1-3 nm, Monodisperse, amorphous	-	14.00%	Sensing and photocatalysis	[03]
Lemon juice	Hydrothermal	200 ℃, 6 h	Formamide	N-CDs 5.7 nm, monodisperse, amorphous	Blue 480/704	31.00%	Bioimaging	[04]

Cabbage	Hydrothermal	140℃, 5 h	Water	2-6 nm, monodisperse, amorphous	Blue 600/485	16.5 %	Bioimaging	[05]
Wheat straw	Hydrothermal	180 ℃, 12 h	Water	2.1 nm, uniformly dispersed, amorphous	Blue 380/470	7.50 %	Sensing and cellular imaging	[06]
Sugarcane bagasse	Hydrothermal	200 °C, 6 h	Water	1.7 nm, uniformly dispersed, amorphous,	Blue	17.98%	Antimicrobials	[07]
Seaweed	Hydrothermal	200 ℃, 4 h	Water	2.2 nm, monodisperse, crystalline	Blue 360/455	1.5 %	Antifungal, anticancer and antifungal activity	[08]
Calotropis procera leaves	Hydrothermal	200 ℃, 4 h	Water	4.3 nm, uniformly dispersed, crystalline	Blue 340/416	71.95%	Sensing	[09]
Aloe barbadensis M.	Microwave	80 W, 1-8 min	Water	3.2 nm, monodisperse, amorphous	Blue 360/434	31.00%	Photocatalysis and Biomedical applications	[10]

Sesame seeds	Microwave	800 W, 10-15 min	Water	N-CDs 5 nm, well dispersed, amorphous	Blue 365/440	8.02 %	Sensing	[11]
Ginkgo fruits	Microwave Hydrothermal	800 W, 15 min 200 °C, 12 h	Water	2.82 nm, less uniformly dispersed 3.81 nm, more uniformly dispersed	-	0.65 % 3.33 %	Bioimaging	[12]
Peanut shell	Pyrolysis	400 ℃, 4 h	-	3.3 nm, well dispersed, amorphous	Blue-green 312/413	10.58%	Sensing	[13]
Carica papaya waste	Pyrolysis	200 ℃, 15 min	-	7.0 nm, amorphous	Blue 340/462	23.70%	Sensing	[14]
Cotton	Pyrolysis followed by microwave treatment	300 ◦C, 2 h followed by 700 W for 12 min	-	4.9 nm, well dispersed, amorphous	Blue 330/460	14.8 %	Bioimaging and sensing	[15]

Wheat straw	Hydrothermal	250 ℃, 10 h	Water	1.7 nm, monodisperse, amorphous	Blue 304/418	9.20 %	Bioimaging	[16]
Ocimum sanctum leaves	Hydrothermal	180 ℃, 4 h	Water	3.0 nm, uniform dispersion amorphous	Green 450/500	9.3 %	Sensing and bioimaging	[17]
Groundnut	Hydrothermal	250 ℃, 6 h	Water	2.5 nm, monodisperse, amorphous	370/445	17.6 %	Sensing and bioimaging	[18]
Rapeseed pollen	Hydrothermal	200 ℃, 24 h	Water	5.2 nm, crystalline	Blue 360/432	7.70 %	Agriculture (plant growth enhancers)	[19]

Table S2. A comparative study of the advantages and disadvantages of the different synthesis routes of the CDs.

Approach	**Carbon precursor**	**Method**	**Advantage**	**Disadvantage**	**Ref.**
Top-down	Carbon shoot, graphite rod, graphite powder, carbon fibers, carbohydrates	Arc discharge	Simple, by control of laser pulse, size can manipulate	Harsh condition, low QY, impurities over synthesis	[20-26]
		Chemical ablation	Inexpensive equipment, CDs can synthesize on large scale, Most accessible	Several synthetic steps, requires toxic chemicals such as strong acid/base, special equipment required,	
		Laser ablation	Simple, by changing experimental parameters, CDs with different sizes and controllable morphology can synthesized	Large raw material, Poor control in size, low QY, modification is necessary	
		Electrochemical exfoliation	High yield, CDs size can manipulate over potential control,	Complex method	
Bottom-up	Organic molecules (organic acid, dopamine, amino acids, glucose,	Hydrothermal	Non-toxic, cost-effective, easy, precursor can be from natural source,	Poor control in size, Long synthesis duration, low yield	

	glycerol), fruit pulp, peel, fruit juice, plant extract, leaves, organic waste (agricultural waste such as wheat straw, rice straw, rice husk)		high quantum efficient		[27-34]
		Pyrolysis	Easy process, wide precursor scope, fast, solvent-free, low cost and can synthesized at large scale	Harsh condition, Non-uniform size distribution	
		Microwave	Fast synthesis, eco-friendly, inexpensive	Poor control in size, ristrict large scale synthesis, high energy cost	

Table S3: Comparison of CDs with other carbon nanomaterials applied in agriculture.

Carbon Nanomaterials	**Features**	**Advantages and Application in Agriculture**	**Disadvantages and Toxicity**	**Ref.**
Carbon Nanotubes (SWCNTs and MWCNTs)	Small size, Tubular shape, High surface area, High tensile strength, Less water soluble, Less biocompatible, Eco-toxic	Seed germination due to small size & tubular shape smooth penetration of seed coat-enhanced water uptake, Better adsorption of water and nutrients, Antimicrobials activity due to mechanical damage, and ROS production, Increase photosynthetic rate via electron transfer, Nutrient and gene delivery system due to small size, tunable surface chemistry and tow toxicity compared to other metal-based nanomaterials, Agro-nanosensors due to luminescence qualities, fast reaction time, and high stability,	Toxicity at high dose, Large size often blocks penetration, Bioaccumulation in plants and entry to the food chain, Penetration to cells leads to deposition followed by blockage of nutrients, Mechanical damage to tissue by piercing effects due to high tensile strength	[35-39]
Graphene and graphene oxide	Small size, Thin sheet structure, Flat shape,	Seed germination and plant growth due to small size and thin sheet structure smooth penetration of seed	Large sheet leads to less translocation hence graphene deposition in cell organelles leads to	

	High strength, Large surface area, High chemical stability, High mechanical stability, Tunable surface chemistry, Low toxicity	coat-enhanced water uptake; Apt. surface chemistry for binding nutrient and water, Delivery vehicle for plant nutrients and genes, Antimicrobials and pesticide activity	bioaccumulation and toxicity, Retarded growth (oxidative stress at higher doses) , Increased heavy metal toxicity as uptake increased due to mechanical damage to cell wall and membrane by large GO sheets	[40-44]
CDs	Ultra-small size, Quasi-spherical shape, Chemical stability, Tunable and stable photoluminescence, Cost-effective production, Remarkable biocompatibility, Negligible toxicity	Improve seed germination since small size and spherical shape-easy seed coat penetration, Improve water and nutrient uptake due to presence of hydrophilic surface groups, Photosynthetic enhancers due to strong fluorescence (Augment light coverage) and enhanced photosynthetic rate via electron transfer, Antimicrobial activity, Agro-nanosensors due to strong fluorescence and high stability	Phytotoxicity at high doses (due to oxidative stress)	[45-49]

Meta/metal oxide nanoparticles	Small size, different types of shape (star, spherical, cube, rod, tripod), Large surface area,	Increase photosynthesis, Diminish MDA and H_2O_2 concentration, Improve the antioxidant enzyme level, Improve the antimicrobial activity against plant pathogen, Ph of the soil can alter, but it varies from soil to soil	Decrease the uptake and translocation of nutrients, Reduces the root hydraulic conductivity, Seedling growth and seed germination can reduce, Decreases the root, and shoot growth, Alter the enzymatic activities and bacterial communities' soils, The phytotoxicity in plant increase due the release of metal ions from MNPs, Aggregation of MNPs can increase toxicity	[50-53]

Table S4: Antimicrobial activity of CDs against various phytopathogens.

Phytopathogen	**Plant disease caused**	**Concentration of CDs for growth inhibition**	**Type of study**	**Ref.**
Fungus *Pseudoperonospora cubensis*	Cucumber downy mildew	40 mg L^{-1}	*In vivo*	[54]
Bacterium *Ralstonia solanacearum*	Bacterial wilt syndrome in tomatoes	10 mg L^{-1}	*In vivo*	[55]
Fungus *Rhizoctonia solani*	Rice blight	300 μg mL^{-1}	*In vitro*	[56]
Fungus *Pyricularia grisea*	Rice blast	300 μg mL^{-1}	*In vitro*	[56]
Fungus *Fusarium oxysporum*	Tomato wilt	50 μL	*In-vitro*	[57]
Bacterium *Pseudomonas aeruginosa*	Root diseases of Arabidopsis and sweet basil	80 μL	*In vitro*	[57]
Bacterium *Pectobacterium carotovorum*	Soft rot and stem rot diseases in Chinese cabbage, potato, tomato etc.	5 mg mL^{-1}	*In vitro*	[58]
Bacterium *Pseudomonas syringae pv. tomato*	Bacterial speck of tomato	5 mg mL^{-1}	*In vitro*	[58]
Bacterium *Agrobacterium tumefaciens*	Crown gall disease in woody plants such as apple, cherry, walnuts, grapevines, rose, etc., and occasionally in cotton, sugar beets, tomatoes, beans and alfalfa.	1 mg mL^{-1}	*In vitro*	[58]
Bacterium *Agrobacterium rhizogenes*	Hairy root disease in dicots such as soybean etc.	1 mg mL^{-1}	*In vitro*	[58]
Fungus *Corynespora cassiicola*	Target spots on cotton, soybean, chilli, papaya, sweet poatato etc.	11 μL mL^{-1}	*In vitro*	[59]
Fungus *Phytophtora nicotianae*	Crown rots on ornamentals, tomato, onion, pepper, citrus plants, etc.	11 μL mL^{-1}	*In vitro*	[59]

Table S5. CD-based detection of various pesticides and herbicides in food samples.

Material	**Precursor of CDs**	**Synthetic rout of CDs**	**Target analyte**	**Samples**	**Technique**	**Linearity**	**LOD**	**Ref.**
CDs	Calotropis procera leaves	Hydrothermal	Isoprothiolane	Fruit (tomato, grape, and apple) and rice	Fluorescence	0.1 mM-0.05 μM	11.58 nM	[60]
CDs	Cauliflower	Hydrothermal	Diazinon, glyphosate, and amicarbazone	Plant, and nutritional product, water	Fluorescence	-	0.25, 0.5, and 2.0 ng mL^{-1} for diazinon, amicarbazone, and glyphosate	[61]
N-CDs	Cellobiose and urea	Hydrothermal	Phosalone,	Jackfruit, pitaya, and water spinach	Fluorescence	0.08-14.0 μg mL^{-1}	28.5 ng mL^{-1}	[62]
N-CDs	DL-malic acid and glycerol	Hydrothermal	Pirimicarb	Tea, apples and cucumbers	Fluorescence	0.5-200 μg mL^{-1}	0.3 μg mL^{-1}	[63]
S,N-CDs	Citric acid	Hydrothermal	Bendiocarb	Juice and water	Chemiluminescence	0.1-10 mg mL^{-1}	0.02 μg mL^{-1}	[64]
S,N,B-CDs	Ginkgo biloba leaves	Hydrothermal	Enitrothion, dithianon, dinoseb	Rice	Fluorescence		Fen, Dit and Din 0.36, 0.28, and 0.66 nM	[65]
N-, S-, Si-CDs	Broccoli leave	Hydrothermal	O,O-dimethyl-O-2,2-dichlorovinyl phosphate	Apple, celery, and cabbage	Fluorescence	0.01-1.0 μM	8.0 nM	[66]
CeO_2-B,N-CDs	Citric acid	Hydrothermal	Methyl-paraoxon	Semen Coicis, panax quinquefolius	Fluorescence	0.015-1.5 mM	24.7 ng mL^{-1}	[67]

				L and tap and lake water,				
Cu-CDs	1-(2-pyridylazo)-2-naphthol (PAN)	Hydrothermal	Thiophanate-methyl	Apple, tomato and water	Fluorescence	0.10-20.00 μmol L^{-1}	2.90 × 10^{-6} μmol L^{-1}	[68]
Ag-CDs	Riboflavin	Hydrothermal	Propanyl, parathion, dimethoate, chlorpyrifos and pyrimicarb,	Rice, carrot, orange and pepper	Fluorescence		250 ng mL^{-1}	[69]
Au-CDs	Sucrose/PEG	Microwave	Malathion	Cabbage	Fluorescence and colorimetric	1×10^{-9}-1×10^{-2} M	0.13×10^{-9} M (fluorescence) and 0.59×10^{-9} M (colorimetric)	[70]
Ca-PEG-CDs	Polyethylene glycol	Pyrolysis	Trifluralin	Soil	Fluorescence		7.89 μM	[71]
CdTe-CDs	Chitosan	Hydrothermal	Glyphosate	Cucumber, Capsicum, Ginger	Fluorescence	0-1000 nM	2.0 pM	[72]
MoS_2-CdS nanospheres and Ag-CDs	Sodium citrate	Hydrothermal	Chlorpyrifos	Fruit and vegetable	ECL	10 nM - 1.0 fM	0.35 fM	[73]
SMIP@Si-CDs	Citric acid	Hydrothermal	Indoxacarb	Apple, tomato and well water	Fluorescence	4-102 nM	1 nM	[74]
CoOOH-CDs	Citric acid	Hydrothermal	2,4-Dichlorophenoxyacetic Acid	Pear juice, human urine, serum and lake water	Fluorescence	-	100 μg L^{-1}	[75]

CDs	Folic acid and p-phenylenediamine	Hydrothermal	Paraoxon	Rice, cabbage and water	Colorimetric and fluorometric	0.001 to 1.0 μg mL^{-1}	0.4 ng mL^{-1}	[76]
CDs-Au@AgNPs	Orange peels	Hydrothermal	Acephate	Baby cabbage and celery cabbag	Colorimetric and fluorometric	0-1800 0-1900 μg L^{-1}	21.0, 16.0 μg L^{-1}	[77]
AChE-ATCh-AgNPs-CDs	Citric acid and urea	Hydrothermal	Carbaryl	Apple juice	Colorimetric and fluorometric	0.025- 2 mU mL^{-1}	0.021 mU mL^{-1} and 0.016 mU mL^{-1}	[78]
N-, B-CDs@GO	-	-	O,O-dimethyl organophosphorus pesticides	Cucumber, cabbage and lettuce	Electrochemical impedance spectroscopy	0.003-0.014 ng mL^{-1}	-	[79]
CDs-ZrO_2	Glucose	Ultrasonication	Methyl parathion	Rice	Adsorptive stripping voltammetry	0.2-48 ng mL^{-1}	0.056 ng mL^{-1}	[80]
N-CDs	Citric acid and ethylenediamine	Hydrothermal	Paraquat	-	DPV	0.1-10 μmol L^{-1}	6.4 nmol L^{-1}	[81]

The physical and chemical properties of CDs are dependent on raw materials, heating temperature, reaction time, solvent effect and heteroatom doping use in the synthesis. Several studies found that the fluorescence property, degree of crystallinity, hydrophilicity, hydrophobicity, and stability of CDs associated with the starting materials. However, the accurate relationship between starting material and distinct properties of CDs is not very clear at present [27, 82-85].

The carbon-based nanomaterials show great potential in agriculture and their toxicity substantially depends on their concentration, growth conditions, and plant species. Moreover, owing to their small size, shape, surface functionalities, and other physicochemical properties, their absorption, and translocation in plants and other organisms raises toxicity concerns, which cannot be overlooked. Although compared to other CNMs, CDs show negligible toxicity and immense potential in agricultural applications, still there is a lack of adequate knowledge. The research in this area requires more efforts to establish a better understanding of the toxicity of CDs [86-88].

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