Title

Cyanobacterial pigment adsorbed on TiO2 thin films

Abstract

The rise in toxicity related to cyanobacterial bloom in freshwater is a current problem that perturbs the trophic chain and risks the ecosystems and human health. Currently, the use of biomass as a potential source of value-added bio-products is an important goal to be achieved in the scope of a sustainable bio-economy. Thus, taking advantage of such bacteria is needed. In the present work, we studied the use of cyanobacterial biomass coming from the Malambo swamp in Colombia as a source of Phycocyanobilin (C-PC) and Chlorophyll-a (Chla) which were used as natural pigments for TiO2 thin films. The concentration obtained of C-PC and Chla extracted were 215 µg/mL and 0.417 µg/mL, respectively. We modeled the natural dye adsorption kinetics on TiO2 thin films through three different models. The Langmuir model showed the best fitting, indicating that the pigment extracted from cyanobacterial biomass can sensitize thin TiO2 film through the formation of a monolayer. Furthermore, the TiO2 films present higher adsorption of C-PC (25.8 mg/g) than Chla (23.3 mg/g). Finally, the adsorption modes were assessed using periodic DFT approximations, which is a remarkable method for studying the structure and properties of solid materials. In terms of binding energies, it was found that the dye shows the strongest interaction with TiO2 through the titanium atom. Thus, the main contribution of this work is directed to explore in deep the natural dye adsorption on TiO2 from both experimental and computational point of view.

Authors

Diaz-Uribe C.; Duran F.; Arcon A.; Vallejo W.; Salazar J.; Schott E.; Zarate X.

Author full names

Diaz-Uribe, Carlos (36909869900); Duran, Freider (57222812373); Arcon, Amado (58137063800); Vallejo, William (35724861200); Salazar, Javier (57364745000); Schott, Eduardo (12766226900); Zarate, Ximena (25653306000)

Author(s) ID

36909869900; 57222812373; 58137063800; 35724861200; 57364745000; 12766226900; 25653306000

Year

2024

Source title

Colloids and Surfaces A: Physicochemical and Engineering Aspects

Volume

688.0

Art. No.

133594

DOI

10.1016/j.colsurfa.2024.133594

Link

https://www.scopus.com/inward/record.uri?eid=2-s2.0-85187206022&doi=10.1016%2fj.colsurfa.2024.133594&partnerID=40&md5=e0121d286171881230ae015b8ece4c92

Affiliations

Grupo de Investigación en Fotoquímica y Fotobiología, Programa de Química, Facultad de Ciencias Básicas, Universidad del Atlántico, Puerto Colombia, 081007, Colombia; Departamento de Química Inorgánica, Facultad de Química y Farmacia, Centro de Energía UC, Centro de Investigación en Nanotecnología y Materiales Avanzados CIEN-UC, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna, Santiago, 4860, Chile; Millenium Nuclei on Catalytic Processes towards Sustainable Chemistry (CSC), Concepción, 4030000, Chile; Instituto de Ciencias Aplicadas, Facultad de Ingeniería, Universidad Autónoma de Chile, Avenida Pedro de Valdivia 425, Santiago, 7500912, Chile

Authors with affiliations

Diaz-Uribe C., Grupo de Investigación en Fotoquímica y Fotobiología, Programa de Química, Facultad de Ciencias Básicas, Universidad del Atlántico, Puerto Colombia, 081007, Colombia; Duran F., Grupo de Investigación en Fotoquímica y Fotobiología, Programa de Química, Facultad de Ciencias Básicas, Universidad del Atlántico, Puerto Colombia, 081007, Colombia; Arcon A., Grupo de Investigación en Fotoquímica y Fotobiología, Programa de Química, Facultad de Ciencias Básicas, Universidad del Atlántico, Puerto Colombia, 081007, Colombia; Vallejo W., Grupo de Investigación en Fotoquímica y Fotobiología, Programa de Química, Facultad de Ciencias Básicas, Universidad del Atlántico, Puerto Colombia, 081007, Colombia; Salazar J., Departamento de Química Inorgánica, Facultad de Química y Farmacia, Centro de Energía UC, Centro de Investigación en Nanotecnología y Materiales Avanzados CIEN-UC, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna, Santiago, 4860, Chile; Schott E., Departamento de Química Inorgánica, Facultad de Química y Farmacia, Centro de Energía UC, Centro de Investigación en Nanotecnología y Materiales Avanzados CIEN-UC, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna, Santiago, 4860, Chile, Millenium Nuclei on Catalytic Processes towards Sustainable Chemistry (CSC), Concepción, 4030000, Chile; Zarate X., Instituto de Ciencias Aplicadas, Facultad de Ingeniería, Universidad Autónoma de Chile, Avenida Pedro de Valdivia 425, Santiago, 7500912, Chile

Author Keywords

Biomass; Chlorophyll-a; Photosynthetic pigments; Phycocyanobilin; Titanium dioxide

Index Keywords

Adsorption; Binding energy; Biomass; Chlorophyll; Dyes; Health risks; Monolayers; Thin films; chlorophyll a; pigment; titanium; titanium dioxide; Chlorophyll a; Cyanobacterial blooms; Cyanobacterial pigments; Dyes adsorptions; Fresh Water; Natural dye; Photosynthetic pigments; Phycocyanobilin; TiO 2 films; TiO 2 thin film;

adsorption; adsorption kinetics; Article; atom; bacterial chromatophore; Colombia; controlled study; cyanobacterium; deprotonation; eutrophication; isotherm; microbial biomass; nonhuman; swamp; Titanium dioxide

Chemicals/CAS

chlorophyll a, 479-61-8; titanium, 7440-32-6; titanium dioxide, 1317-70-0, 1317-80-2, 13463-67-7, 51745-87-0

Funding Details

Anillos de Ciencia y Tecnología, (ACT210057); Fondo Nacional de Desarrollo Científico y Tecnológico, FONDECYT, (1231194, 3240414, 1241917); Fondo Nacional de Desarrollo Científico y Tecnológico, FONDECYT

Funding Texts

C.D-U., A.A., F.D., and W.V., thanks to Universidad del Atlántico. This work was funded by ANID , ANID/FONDAP/1523A0006; FONDECYT 1241917, 1231194 , FONDECYT postdoctorado 3240414 and the Anillos de Ciencia y Tecnología ACT210057 .

References

Lurling M., Van Oosterhout F., Faassen E., Eutrophication and warming boost cyanobacterial biomass and microcystins, Toxins, 9, (2017); Zhang Y., Luo P., Zhao S., Kang S., Wang P., Zhou M., Lyu J., Control and remediation methods for eutrophic lakes in the past 30 years, Water Sci. Technol.: J. Int. Assoc. Water Pollut. Res., 81, pp. 1099-1113, (2020); Hwang S.J., Eutrophication and the ecological health risk, Int. J. Environ. Res. Public Health, 17, pp. 1-6, (2020); Huisman J., Codd G.A., Paerl H.W., Ibelings B.W., Verspagen J.M.H., Visser P.M., Cyanobacterial blooms, Nat. Rev. Microbiol., 8, 16, pp. 471-483, (2018); Puyana M., Acosta A., Bernal-Sotelo K., Velasquez-Rodriguez T., Ramos F., Spatial scale of cyanobacterial blooms in Old Providence Island, Colombian Caribbean, Univ. Sci., 20, pp. 83-105, (2015); Caly L.F., Rodriguez D.C., Penuela G.A., Monitoring of cyanobacteria and cyanotoxins in a Colombian tropical reservoir, Environ. Sci. Pollut. Res., pp. 1-13, (2022); Garg A., Chopra L., Dye Waste: a significant environmental hazard, Mater. Today.: Proc., 48, pp. 1310-1315, (2022); Guo Q., Zhou C., Ma Z., Yang X., Fundamentals of TiO2 photocatalysis: concepts, mechanisms, and challenges, Adv. Mater., 31, (2019); Anucha C.B., Altin I., Bacaksiz E., Stathopoulos V.N., Titanium dioxide (TiO_2)-based photocatalyst materials activity enhancement for contaminants of emerging concern (CECs) degradation: In the light of modification strategies, Chem. Eng. J. Adv., 10, (2022); Dong H., Zeng G., Tang L., Fan C., Zhang C., He X., He Y., An overview on limitations of TiO2-based particles for photocatalytic degradation of organic pollutants and the corresponding countermeasures, Water Res., 79, pp. 128-146, (2015); Zarate X., Schott-Verdugo S., Rodriguez-Serrano A., Schott E., The nature of the donor motif in acceptor-bridge-donor dyes as an influence in the electron photo-injection mechanism in DSSCs, J. Phys. Chem. A, 120, pp. 1613-1624, (2016); Zarate X., Claveria-Cadiz F., Arias-Olivares D., Rodriguez-Serrano A., Inostroza N., Schott E., Effects of the acceptor unit in dyes with acceptor–bridge–donor architecture on the electron photo-injection mechanism and aggregation in DSSCs, Phys. Chem. Chem. Phys., 18, pp. 24239-24251, (2016); Hu K., Robson K.C.D., Beauvilliers E.E., Schott E., Zarate X., Arratia-Perez R., Berlinguette C.P., Meyer G.J., Intramolecular and lateral intermolecular hole transfer at the sensitized TiO2 interface, J. Am. Chem. Soc., 136, pp. 1034-1046, (2014); Gomez T., Zarate X., Schott E., Arratia-Perez R., Role of the main adsorption modes in the interaction of the dye [COOH–TPP-Zn(II)] on a periodic TiO_2 slab exposing a rutile (110) surface in a dye-sentized solar cell, RSC Adv., 4, pp. 9639-9646, (2014); Nandan Arka G., Bhushan Prasad S., Singh S., Comprehensive study on dye sensitized solar cell in subsystem level to excel performance potential: a review, Sol. Energy, 226, pp. 192-213, (2021); Rahimi N., Pax R.A., Gray E.M.A., Review of functional titanium oxides. I: TiO_2 and its modifications, Prog. Solid State Chem., 44, pp. 86-105, (2016); Hug H., Bader M., Mair P., Glatzel T., Biophotovoltaics: natural pigments in dye-sensitized solar cells, Appl. Energy, 115, pp. 216-225, (2014); Richhariya G., Kumar A., Tekasakul P., Gupta B., Natural dyes for dye sensitized solar cell: a review, Renew. Sustain. Energy Rev., 69, pp. 705-718, (2017); Komarek J., Delimitation of the family Oscillatoriaceae (Cyanobacteria) according to the modern polyphasic approach (introductory review), Braz. J. Bot., 2, 41, pp. 449-456, (2017); Demoulin C.F., Lara Y.J., Cornet L., Francois C., Baurain D., Wilmotte A., Javaux E.J., Cyanobacteria evolution: Insight from the fossil record, Free Radic. Biol. Med., 140, pp. 206-223, (2019); Wood J.L., Miller C.D., Sims R.C., Takemoto J.Y., Biomass and phycocyanin production from cyanobacteria dominated biofilm reactors cultured using oilfield and natural gas extraction produced water, Algal Res., 11, pp. 165-168, (2015); Kathiravan A., Chandramohan M., Renganathan R., Sekar S., Cyanobacterial chlorophyll as a sensitizer for colloidal TiO_2, Spectrochim. Acta Part A: Mol. Biomol. Spectrosc., 71, pp. 1783-1787, (2009); Rockwell N.C., Martin S.S., Li F.W., Mathews S., Lagarias J.C., The phycocyanobilin chromophore of streptophyte algal phytochromes is synthesized by HY2, New Phytol., 214, (2017); Hui Tu P., Heng Yao Y., Li Li Y., Liu B., Conformational flexibility of phycocyanobilin: Monte-Carlo and DFT study, J. Mol. Struct.: Theochem., 894, pp. 9-13, (2009); Bjorn L.O., Papageorgiou G.C., Blankenship, Govindjee R.E., A viewpoint: why chlorophyll a?, Photosynth. Res., 99, pp. 85-98, (2009); Li Y., He N., Hou J., Xu L., Liu C., Zhang J., Wang Q., Zhang X., Wu X., Factors influencing leaf chlorophyll content in natural forests at the biome scale, Front. Ecol. Evol., 6, (2018); Ludin N.A., Al-Alwani

Mahmoud A.M., Bakar Mohamad A., Kadhum A.H., Sopian K., Abdul Karim N.S., Review on the development of natural dye photosensitizer for dye-sensitized solar cells, Renew. Sustain. Energy Rev., 31, pp. 386-396, (2014); R. M F.C., Matteocci F., Di Carlo A., Chlorophylls and xanthophylls of crop plants as dyes for Dye-Sensitized Solar Cells (DSSC), J. Plant Sci. Phytopathol., 1, pp. 087-094, (2017); Kathiravan A., Renganathan R., Photosensitization of colloidal TiO2 nanoparticles with phycocyanin pigment, J. Colloid Interface Sci., 335, pp. 196-202, (2009); Cerda, Phycocyanin as potential natural dye for its use in photovoltaic cells, J. Appl. Solut. Chem. Model., (2013); Knez Z., Hrncic M.K., Colnik M., Skerget M., Chemicals and value added compounds from biomass using sub- and supercritical water, J. Supercrit. Fluids, 133, pp. 591-602, (2018); Ruales-Salcedo A.V., Fontalvo J., Prado-Rubio O.A., Grisales-Diaz V.H., Morales-Rodriguez R., Production of high-added value compounds from biomass, Biofuels Bioref.: Vol. 1: Curr. Technol. Biomass Convers., pp. 381-445, (2022); De S., Burange A.S., Luque R., Conversion of biomass-derived feedstocks into value-added chemicals over single-atom catalysts, Green. Chem., 24, pp. 2267-2286, (2022); de Farias Silva C.E., Bertucco A., Bioethanol from Microalgal Biomass: A Promising Approach in Biorefinery, Braz. Arch. Biol. Technol., 62, (2019); Mehariya S., Fratini F., Lavecchia R., Zuorro A., Green extraction of value-added compounds form microalgae: a short review on natural deep eutectic solvents (NaDES) and related pre-treatments, J. Environ. Chem. Eng., 9, (2021); Dell'Edera M., Lo Porto C., De Pasquale I., Petronella F., Curri M.L., Agostiano A., Comparelli R., Photocatalytic TiO2-based coatings for environmental applications, Catal. Today, 380, pp. 62-83, (2021); Anselmi C., Mosconi E., Pastore M., Ronca E., De Angelis F., Adsorption of organic dyes on TiO2 surfaces in dye-sensitized solar cells: interplay of theory and experiment, Phys. Chem. Chem. Phys., 14, pp. 15963-15974, (2012); Pastore M., De Angelis F., Aggregation of organic dyes on TiO2 in dye-sensitized solar cells models: an Ab initio investigation, ACS Nano, 4, pp. 556-562, (2010); Zanjanchi F., Beheshtian J., Natural pigments in dye-sensitized solar cell (DSSC): a DFT-TDDFT study, J. Iran. Chem. Soc., 16, pp. 795-805, (2019); Jafari S., Sillanpaa M., Adsorption of dyes onto modified titanium dioxide, Adv. Water Treat.: Adsorpt., pp. 85-160, (2020); Zolkepli Z., Lim A., Ekanayake P., Tennakoon K., Efficiency Enhancement of Cocktail Dye of Ixora coccinea and Tradescantia spathacea in DSSC, J. Biophys., 2015, (2015); Calogero G., Yum J.-H., Sinopoli A., Di Marco G., Gratzel M., Nazeeruddin M.K., Anthocyanins and betalains as light-harvesting pigments for dye-sensitized solar cells, Sol. Energy, 86, pp. 1563-1575, (2012); Dhanasekaran P., Marimuthu R., Simultaneous effect of activated carbon and chlorophyll pigment from leaves of acacia nilotica on the enhancement of electron transfer in DSSC applications, Mater. Res. Express, 9, (2022); Arjmand F., Rashidi Ranjbar Z., Fatemi E. G H., Effect of dye complex structure on performance in DSSCs; an experimental and theoretical study, Heliyon, 8, (2022); Diaz-Uribe C., Vallejo W., Romero E., Villareal M., Padilla M., Hazbun N., Munoz-Acevedo A., Schott E., Zarate X., TiO2 thin films sensitization with natural dyes extracted from Bactris guineensis for photocatalytic applications: experimental and DFT study, J. Saudi Chem. Soc., 24, pp. 407-416, (2020); Patino-Camelo K., Diaz-Uribe C., Gallego-Cartagena E., Vallejo W., Martinez V., Quinones C., Hurtado M., Schott E., Cyanobacterial biomass pigments as natural sensitizer for TiO2 Thin Films, Int. J. Photoenergy, 2019, (2019); Jeffrey S.W., Humphrey G.F., New spectrophotometric equations for determining chlorophylls a, b, c1 and c2 in higher plants, algae and natural phytoplankton, Biochem. Physiol. Pflanz., 167, pp. 191-194, (1975); Fernandez J.A., Suan A., Ramirez J.C., Robles J., Salcedo J.C., Pedroza A.M., Daza C.E., Treatment of real wastewater with TiO2-films sensitized by a natural-dye obtained from Picramnia sellowii, J. Environ. Chem. Eng., 4, pp. 2848-2856, (2016); Quinones C., Ayala J., Vallejo W., Methylene blue photoelectrodegradation under UV irradiation on Au/Pd-modified TiO2 films, Appl. Surf. Sci., 257, (2010); Saravanan A., Sundararaman T.R., Jeevanantham S., Karishma S., Kumar P.S., Yaashikaa P.R., Effective adsorption of Cu(II) ions on sustainable adsorbent derived from mixed biomass (Aspergillus campestris and agro waste): Optimization, isotherm and kinetics study, Groundw. Sustain. Dev., 11, (2020); Ayachi F., Z. Kyzas G., Aatrous M., Sakly A., Ben Lamine A., Evaluating the adsorption of Ni(II) and Cu(II) on spirulina biomass by statistical physics formalism, J. Ind. Eng. Chem., 80, pp. 461-470, (2019); Ayawei N., Ebelegi A.N., Wankasi D., Modelling and interpretation of adsorption isotherms, J. Chem., 2017, (2017); Wong Y.C., Szeto Y.S., Cheung W.H., Mckay G., Adsorption of acid dyes on chitosan-equilibrium isotherm analyses, Process Biochem., 39, pp. 693-702, (2004); Diaz-Uribe C., Walteros L., Duran F., Vallejo W., Bohorquez A.R.R., Prosopis juliflora seed waste as biochar for the removal of blue methylene: a thermodynamic and kinetic study, ACS Omega, (2022); Benjelloun M., Miyah Y., Akdemir Evrendilek G., Zerrouq F., Lairini S., Recent advances in adsorption kinetic models: their application to dye types, Arab. J. Chem., 14, (2021); Neese F., Software update: the ORCA program system, version 4.0, Wiley Interdisciplinary Reviews: Computational Molecular Science, 8, (2018); Perdew J.P., Burke K., Ernzerhof M., Generalized gradient approximation made simple, Phys. Rev. Lett., 77, pp. 3865-3868, (1996); Dal Corso A., Pseudopotentials periodic table: from H to Pu, Comput. Mater. Sci., 95, pp. 337-350, (2014); Grimme S., Ehrlich S., Goerigk L., Effect of the damping function in dispersion corrected density functional theory, J. Comput. Chem., 32, pp. 1456-1465, (2011); Scaranto J., Mallia G., Harrison N.M., An efficient method for computing the binding energy of an adsorbed molecule within a periodic approach. The application to vinyl fluoride at rutile TiO2(1 1 0) surface, Comput. Mater. Sci., 50, pp. 2080-2086, (2011); Horn H., Schwerdtfeger C.F., Meagher E.P., Refinement of the structure of anatase at several temperatures, Z. Krist., 136, pp. 273-281, (1972); Srivastava R., Prajapati R., Kanda T., Yadav S., Singh N., Yadav S., Mishra R., Atri N., Phycochemistry and bioactivity of cyanobacterial secondary metabolites, Mol. Biol. Rep., 49, pp. 11149-11167, (2022); Fu H., Zeng T., Zhao Y., Luo T., Deng H., Meng C., Luo J., Wang C., Identification of chlorophyll metabolism- and photosynthesis-related genes regulating green flower color in chrysanthemum by integrative transcriptome and weighted correlation network analyses, Genes, 12, 449 12, (2021); Li Y., Zhang Z., Paciulli M., Abbaspourrad A., Extraction of phycocyanin—a natural blue colorant from dried spirulina biomass: influence of processing parameters and extraction techniques, J. Food Sci., 85, pp. 727-735, (2020); Lee S.Y., Stuckey D.C., Separation and biosynthesis of value-added compounds from food-processing wastewater: towards sustainable wastewater resource recovery, J. Clean. Prod., 357, (2022); Giovannetti R., Alibabaei L., Zannotti M., Ferraro S., Petetta L., HPLC-DAD-ESI/MS identification of light harvesting and light screening pigments in the lake sediments at edmonson point, Sci. World J., 2013, (2013); Ji B., Wang J., Song H., Chen W., Removal of methylene blue from aqueous solutions using biochar derived from a fallen leaf by slow pyrolysis: behavior and mechanism, J. Environ. Chem. Eng., 7, (2019); Al-Ghouti M.A., Da'ana D.A., Guidelines for the use and interpretation of adsorption isotherm models: a review, J. Hazard Mater., 393, (2020); Ammar A.M., Mohamed H.S.H., Yousef M.M.K., Abdel-Hafez G.M., Hassanien A.S., Khalil A.S.G., Dye-Sensitized Solar Cells (DSSCs) based on extracted natural dyes, J. Nanomater., 2019, (2019); Kim T.Y., Kim J.H., Kim H.B., Park K.H., Lee J.W., Cho S.Y., Adsorption and kinetics properties of TiO 2 photoelecrode using natural paprika oleoresin (Capsicum annuum L.) dye for dye-sensitized solar cells, Int. J. Electrochem. Sci., 13, pp. 3935-3947, (2018); Vallejo W., DIaz-Uribe C., Rios K., Methylene blue photocatalytic degradation under visible irradiation on In2S3 synthesized by chemical bath deposition, Adv. Phys. Chem., 2017, (2017); Collazzo G.C., Jahn S.L., Foletto E.L., Removal of direct black 38 dye by adsorption and photocatalytic degradation on TiO2 prepared at low temperature, Lat. Am. Appl. Res., 42, pp. 55-60, (2012); Perdew J.P., Burke K., Generalized gradient approximation for the exchange-correlation hole of a many-electron system, Phys. Rev. B, Condens. Matter, 54, pp. 16533-16539, (1996); Weigend F., Ahlrichs R., Balanced basis sets of split valence, triple zeta valence and quadruple zeta valence quality for H to Rn: design and assessment of accuracy, Phys. Chem. Chem. Phys., 7, pp. 3297-3305, (2005); Giannozzi P., Baroni S., Bonini N., Calandra M., Car R., Cavazzoni C., Ceresoli D., Chiarotti G.L., Cococcioni M., Dabo I., Corso A.D., Gironcoli S., Fabris S., Fratesi G., Gebauer R., Gerstmann U., Gougoussis C., Kokalj A., Lazzeri5 M., Martin-Samos L., Marzari N., Mauri F., Mazzarello R., Paolini S., Pasquarello A., Paulatto L., Sbraccia C., Scandolo S., Sclauzero G., Seitsonen A.P., Smogunov A., Umari P., Wentzcovitch R.M., QUANTUM ESPRESSO: a modular and open-source software project for quantum simulations of materials, J. Phys.: Condens. Matter, 21, (2009); Momma K., Izumi F., VESTA 3 for three-dimensional visualization of crystal, volumetric and morphology data, J. Appl. Crystallogr., 44, pp. 1272-1276, (2011)

Correspondence Address

C. Diaz-Uribe; Grupo de Investigación en Fotoquímica y Fotobiología, Programa de Química, Facultad de Ciencias Básicas, Universidad del Atlántico, Puerto Colombia, 081007, Colombia; email: carlosdiaz@mail.uniatlantico.edu.co; E. Schott; Departamento de Química Inorgánica, Facultad de Química y Farmacia, Centro de Energía UC, Centro de Investigación en Nanotecnología y Materiales Avanzados CIEN-UC, Pontificia Universidad Católica de Chile, Santiago, Avenida Vicuña Mackenna, 4860, Chile; email: edschott@uc.cl

Publisher

Elsevier B.V.

ISSN

09277757

CODEN

CPEAE

Language of Original Document

English

Abbreviated Source Title

Colloids Surf. A Physicochem. Eng. Asp.

Document Type

Article

Publication Stage

Final

Source

Scopus

EID

2-s2.0-85187206022