**Supplementary Information**

# Embracing the Allelopathic Potential of Invasive Aquatic Plants to Manipulate Freshwater Ecosystems

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**Table S1. Previous Work on allelopathic effects of aquatic plants on algae and cyanobacteria.** This table outlines all the current work which has been undertaken concerning the allelopathic effect of aquatic plants on algae and cyanobacteria. It outlines the species of plant used, the method applied to the plant material, the allelochemicals found to be contained within the relevant species, and the algae and/or cyanobacteria the plant was shown to affect. This table is adapted from Mohamed, 2017, with additional experimental results added. The list of references cited follow the table.

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| *Species* | *Plant material tested* | *Allelochemicals Contained* | *Algae and/or Cyanobacteria Inhibited* | *Reference* |
| *Acorus calamus* | Extract | Phenylpropanes | *Anabaena flos-aquae, Aphanizomenon flos-aquae, Microcystis aeruginosa* | (Greca *et al.*, 1989; Zhang, 2015; Zhang, Zhang and Li, 2016) |
| *Acorus gramineus* | Extract | Phenylpropanes | *Microcystis aeruginosa* | (Greca *et al.*, 1989; Nakai, S., Zou, G., Okuda, T., Tsai, T.-Y., Song, X., Nishijima, W., Okada, 2010) |
| *Acorus tatarinowii* | Exudate | Phenylpropanes | *Anabaena flos-aquae, Synecococcus leopoliensis, Microcystis aeruginosa* | (Greca *et al.*, 1989; He and Wang, 2001) |
| *Arundo donax* | Extract | Gramine (N,N-dimethyl-3-amino-methylindole) | *Microcystis aeruginosa* | (Hong, Hu and Li, 2008; Hong, Huang and Hu, 2009) |
| *Eleocharis acicularis* | Co-cultivation | Unknown | *Anabaena flos-aquae, Microcystis aeruginosa, Phormidium tenue* | (Nakai *et al.*, 1999) |
| *Phragmites australis* | Extract | Unknown | *Microcystis aeruginosa, Scenedesmus acutus* | (Nakai, S., Zou, G., Okuda, T., Tsai, T.-Y., Song, X., Nishijima, W., Okada, 2010; Chicalote-Castillo, Ramirez-Garcia and Macias-Rubalcava, 2017) |
| *Phragmites communis* | Extract Fraction | Ethyl 2-methylacetoacetate, phenolic acids (p-coumaric acid, ferulic acid), caffeic acid (gallic acid), fatty acid (stearic acid) | *Microcystis aeruginosa, Phormidium* sp. | (Zhou *et al.*, 2004; Li and Hu, 2005) |
| *Scirpus tabernaemontani* | Extract | Unknown | *Microcystis aeruginosa* | (Nakai, S., Zou, G., Okuda, T., Tsai, T.-Y., Song, X., Nishijima, W., Okada, 2010) |
| *Thalia dealbata* | Extract | Unknown | *Anabaena flos-aquae, Microcystis aeruginosa* | (Zhang *et al.*, 2011) |
| *Typha latifolia* | Extract | Steroids, fatty acids. | *Anabaena flos-aquae, Microcystis aeruginosa* | (Aliotta *et al.*, 1990) |
| *Typha angustifolia* | Extract | Phenic acids (o-hydroxycinnamic acid, syringic acid and isoferulic acid | *Synechococcus leopoliensis* | (Zhang, Hu and Zhang, 2011) |
| *Brasenia scherberi* | Extract | Unknown | *Anabaena flos-aquae* | (Elakovich and Wooten, 1987) |
| *Cambomba caroliniana* | Co-cultivation | Unknown | *Anabaena flos-aquae, Microcystis aeruginosa, Phormidium tenue* | (Nakai *et al.*, 1999) |
| *Eichhornia crassipes* | Extract | N-phenyl-1-naphthylamine, linoleic acid, benzoindenone | *Anabaena azollae, Microcystis aeruginosa* | (Wu *et al.*, 2012) |
| *Lemma minor* | Co-cultivation | Unknown | *Microcystis aeruginosa* | (Jang, Ha and Takamura, 2007) |
| *Nelumbo nucifera* | Extract | Propanamide | *Microcystis aeruginosa* | (Hong, Hu and Li, 2008; He, L.S., Meng, F.L., Diao, X.J., Li, Y.W., Meng, R., Xi, B.D., Shu, 2013) |
| *Pista stratiotes* | Extract | Polyphenols, linoleic acid, linolenic acid, fatty acids, steroidal ketones | *Microcystis aeruginosa* | (Aliotta *et al.*, 1991; Wu *et al.*, 2013) |
| *Stratiotes aloides* | Extract | Moderately lipophilic non- phenolic compounds | *Anabaena variabilis, Microcystis aeruginosa, Synechococcus elongatus* | (Mulderij *et al.*, 2007; Mohamed and Al Shehri, 2010) |
| *Ceratophyllum demersum* | Extract | Element sulfides, labile sulfur compounds | *Microcystis aeruginosa, Anabaena* sp.*, Synechococcus elongatus, A. variabilis.* | (Gross, Erhard and Iványi, 2003; Hong, Hu and Li, 2008) |
| *Egeria densa* | Co-cultivation | Unknown | *Cyanobacteria* | (Nakai *et al.*, 1999) |
| *Elodea canadensis* | Exudate/Extract | Phenolic compounds | *Epiphytic cyanobacteria* | (Erhard and Gross, 2006) |
| *Elodea nuttalii* | Exudate/Extract | Phenolic compounds | *Epiphytic cyanobacteria* | (Erhard and Gross, 2006) |
| *Hydrilla verticillata* | Exudate/Extract | Phenolic compound (vanillic acid, protocatechic acid, ferulic acid, caffeic acid) | *Microcystis aeruginosa* | (Wang, L.X., Zhang, L., Zhang, Y.X., Jin, C.Y., Lu, C.M., Wu, 2006; Y. Gao, B.Liu, D.Xu, Q. Zhou, C. Hu, F. Ge, L. Zhang, 2011; Zhang *et al.*, 2012) |
| *Limnophila sessiliflora* | Co-cultivation | Unknown | *Cyanobacteria* | (Nakai *et al.*, 1999) |
| *Myriophyllum brasiliense* | Extract | Polyphenol-like alleochemicals | *Microcystis aeruginosa* | (Saito *et al.*, 1989) |
| *Myriophyllum spicatum* | Co-cultivation | Tellimagrandin II, pyrogallic acid, gallic acid, ellagic acid, (+)-catechin | *Microcystis aeruginosa* | (Nakai, Yamada and Hosomi, 2005; Zhu *et al.*, 2010) |
| *Myriophyllum verticillatum* | Extract | a-asarone, phenylpropane, glycoside-like allelochemicals | *Microcystis aeruginosa, Limnothrix redeke* | (Aliotta *et al.*, 1992; Hilt, 2006) |
| *Najas marina* | Extract | Hydrophilic and moderately lipophilic allelochemicals | *Anabaena variabilis, Synechococcus elongatus* | (Gross, Erhard and Iványi, 2003) |
| *Potamogeton malaianus* | Co-cultivation/Exudate | Diterpenes, linolenic acid | *Microcystis aeruginosa* | (Hu and Hong, 2008; Zhang, S.H., Cheng, S.P., Wang, H.Q., He, F., Wu, 2009) |
| *Potamogeton maackianus* | Co-cultivation/Exudate | Diterpenes, linolenic acid | *Microcystis aeruginosa* | (Hu and Hong, 2008; Zhang, S.H., Cheng, S.P., Wang, H.Q., He, F., Wu, 2009) |
| *Potamogeton pectinastusm* | Co-cultivation/Exudate | Diterpenes, linolenic acid | *Microcystis aeruginosa* | (Hu and Hong, 2008; Zhang, S.H., Cheng, S.P., Wang, H.Q., He, F., Wu, 2009) |
| *Potamogeton pusillus* | Exudate | Unknown | *Microcystis aeruginosa* | (Takeda *et al.*, 2011) |
| *Potamogeton lucens* | Extract | Unknown | *Anabaena variabilis* | (Jasser, 1995) |
| *Potamogeton crispus* | Co-cultivation/Exudate/Extract | Unknown | *Anabaena variabilis Microcystis aeruginosa* | (Pakdel *et al.*, 2013) |
| *Potamogeton oxyphyllys* | Co-cultivation/Exudate/Extract | Unknown | *Anabaena variabilis Microcystis aeruginosa* | (Nakai *et al.*, 1999) |
| *Vallisneria denseserrulata* | Co-cultivation | 2-ethyl-3- methylmaldeimide, carotene derivatives | *Microcystis aeruginosa* | (Xian *et al.*, 2006; Gao, Y., Liu, B., Xu, D., Zhou, Q., Hu, C., Ge, F., Zhang, L., Wu, 2011) |
| *Chara aspra* | Extract | 4-methylthio-1,2-dithiolane and 5-hydroxy-1,2,3-trithiane. | *Anabaena cylindrica, A. torulosa, Anabaenopsis elenkinii, M. aeruginosa, Synechococcus* sp. | (Berger, J., Schagerl, 2004; Złoch *et al.*, 2018) |
| *Chara globularis* | Extract | 4-methylthio-1,2-dithiolane and 5-hydroxy-1,2,3-trithiane. | *Anabaena cylindrica, A. torulosa, Anabaenopsis elenkinii, M. aeruginosa* | (Berger, J., Schagerl, 2004; Złoch *et al.*, 2018) |
| *Nitellopsis obtuse* | Extract | 4-methylthio-1,2-dithiolane and 5-hydroxy-1,2,3-trithiane. | *Anabaena cylindrica, A. torulosa, Anabaenopsis elenkinii, M. aeruginosa* | (Berger, J., Schagerl, 2004; Złoch *et al.*, 2018) |
| *Nitella gracilis* | Extract | 4-methylthio-1,2-dithiolane and 5-hydroxy-1,2,3-trithiane. | *Anabaena cylindrica, A. torulosa, Anabaenopsis elenkinii, M. aeruginosa* | (Berger, J., Schagerl, 2004; Złoch *et al.*, 2018) |
| *Chara australis* | Extract/Exudate | Unknown | *Anabaena variabilis* | (Pakdel *et al.*, 2013) |
| *Chara hispida* | Exudate | Unknown | *Pseudanabaena* sp. | (Rojo, Segura and Rodrigo, 2013) |
| *Chara vulgaris* | Exudate | Unknown | *Pseudanabaena* sp. | (Rojo, Segura and Rodrigo, 2013) |
| *Chara baltica* | Exudate | Unknown | *Pseudanabaena* sp.*, Synechococcus* sp. | (Rojo, Segura and Rodrigo, 2013; Złoch *et al.*, 2018) |
| *Nitella hyalina* | Exudate | Unknown | *Pseudanabaena* sp. | (Rojo, Segura and Rodrigo, 2013) |
| *Alternanthera philoxeroides* | Pure Chemicals | Coumarin, L-hydroxybenzoic acid, protocatechuic acid, stearic acid, and L-aminobenz enesulfonic acid | *Chlorella pyrenoidosa* | (Zuo *et al.*, 2016) |
| *Chara canescens* | Extract | Unknown | *Synechococcus* sp. | (Złoch *et al.*, 2018) |
| *Schoenoplectus californicus* | Extract | Unknown | *Microcystis aeruginosa, Scenedesmus acutus* | (Chicalote-Castillo, Ramirez-Garcia and Macias-Rubalcava, 2017) |

# **References**

Aliotta, G. *et al.* (1990) ‘In vitro algal growth inhibition by phytotoxins of Typha latifolia L.’, *Journal of Chemical Ecology*. Kluwer Academic Publishers-Plenum Publishers, 16(9), pp. 2637–2646. doi: 10.1007/BF00988075.

Aliotta, G. *et al.* (1991) ‘Potential allelochemicals from Pistia stratiotes L.’, *Journal of Chemical Ecology*. Kluwer Academic Publishers-Plenum Publishers, 17(11), pp. 2223–2234. doi: 10.1007/BF00988003.

Aliotta, G. *et al.* (1992) ‘Three biologically active phenylpropanoid glucosides from Myriophyllum verticillatum’, *Phytochemistry*. Pergamon, 31(1), pp. 109–111. doi: 10.1016/0031-9422(91)83017-F.

Berger, J., Schagerl, M. (2004) ‘Allelopathic activity of Characeae’, *Biologia - Section Botany*, 59(1), pp. 9–15.

Chicalote-Castillo, D., Ramirez-Garcia, P. and Macias-Rubalcava, M. L. (2017) ‘Allelopathic effects among selected species of phytoplankton and macrophytes’, *Journal of Environmental Biology*, 38(6(SI)), pp. 1221–1227. doi: 10.22438/jeb/38/6(SI)/07.

Elakovich, S. D. and Wooten, J. W. (1987) ‘An examination of the phytotoxicity of the water shield, Brasenia schreberi’, *Journal of Chemical Ecology*. Kluwer Academic Publishers-Plenum Publishers, 13(9), pp. 1935–1940. doi: 10.1007/BF01014676.

Erhard, D. and Gross, E. M. (2006) ‘Allelopathic activity of Elodea canadensis and Elodea nuttallii against epiphytes and phytoplankton’, *Aquatic Botany*, 85(3), pp. 203–211. doi: 10.1016/j.aquabot.2006.04.002.

Gao, Y., Liu, B., Xu, D., Zhou, Q., Hu, C., Ge, F., Zhang, L., Wu, B. (2011) ‘Phenolic compounds exuded from two submerged freshwater macrophytes and their allelopathic effects on microcystis aeruginosa’, *Polish Journal of Environmental Studies*, 20(5), pp. 1153–1159.

Greca, M. Della *et al.* (1989) ‘Allelochemical activity of phenylpropanes from Acorus gramineus’, *Phytochemistry*. Pergamon, 28(9), pp. 2319–2321. doi: 10.1016/S0031-9422(00)97975-5.

Gross, E. M., Erhard, D. and Iványi, E. (2003) ‘Allelopathic activity of Ceratophyllum demersum L. and Najas marina ssp. intermedia (Wolfgang) Casper’, *Hydrobiologia*, 506–509(1–3), pp. 583–589. doi: 10.1023/B:HYDR.0000008539.32622.91.

He, L.S., Meng, F.L., Diao, X.J., Li, Y.W., Meng, R., Xi, B.D., Shu, J. M. (2013) ‘Allelopathic effect of Nelumbo nucifera stem and leaf tissue extract on the growth of Microcystis aeruginosa and Scenedesmus quadricanda.’, *Huan Jing Ke Xue*, 34, pp. 2637–2641.

He, C. Q. and Wang, C. K. (2001) ‘Allelopathic effect of Acorus tatarinowii upon algae.’, *Journal Of Environmental Sciences China*, 13(4), pp. 481–484. doi: 10.1016/j.watres.2012.10.003.

Hilt, S. (2006) ‘Allelopathic inhibition of epiphytes by submerged macrophytes’, *Aquatic Botany*. Elsevier, 85(3), pp. 252–256. doi: 10.1016/j.aquabot.2006.05.004.

Hong, Y., Hu, H.-Y. and Li, F.-M. (2008) ‘Physiological and biochemical effects of allelochemical ethyl 2-methyl acetoacetate (EMA) on cyanobacterium Microcystis aeruginosa’, *Ecotoxicology and Environmental Safety*. Academic Press, 71(2), pp. 527–534. doi: 10.1016/J.ECOENV.2007.10.010.

Hong, Y., Huang, J.-J. and Hu, H.-Y. (2009) ‘Effects of a Novel Allelochemical Ethyl 2-Methyl Acetoacetate (EMA) on the Ultrastructure and Pigment Composition of Cyanobacterium Microcystis aeruginosa’, *Bulletin of Environmental Contamination and Toxicology*. Springer-Verlag, 83(4), pp. 502–508. doi: 10.1007/s00128-009-9795-4.

Hu, H. and Hong, Y. (2008) ‘Algal-bloom control by allelopathy of aquatic macrophytes - A review’, *Frontiers of Environmental Science and Engineering in China*, 2(4), pp. 421–438. doi: 10.1007/s11783-008-0070-4.

Jang, M.-H., Ha, K. and Takamura, N. (2007) ‘Reciprocal allelopathic responses between toxic cyanobacteria (Microcystis aeruginosa) and duckweed (Lemna japonica)’, *Toxicon*. Pergamon, 49(5), pp. 727–733. doi: 10.1016/J.TOXICON.2006.11.017.

Jasser, I. (1995) ‘The influence of macrophytes on a phytoplankton community in experimental conditions’, *Hydrobiologia*. Kluwer Academic Publishers, 306(1), pp. 21–32. doi: 10.1007/BF00007855.

Li, F.-M. and Hu, H.-Y. (2005) ‘Isolation and characterization of a novel antialgal allelochemical from Phragmites communis.’, *Applied and environmental microbiology*. American Society for Microbiology, 71(11), pp. 6545–53. doi: 10.1128/AEM.71.11.6545-6553.2005.

Mohamed, Z. A. (2017) ‘Macrophytes-cyanobacteria allelopathic interactions and their implications for water resources management: A review’, *Limnologica*. Elsevier GmbH., 63, pp. 122–132. doi: 10.1016/j.limno.2017.02.006.

Mohamed, Z. A. and Al Shehri, A. M. (2010) ‘Differential responses of epiphytic and planktonic toxic cyanobacteria to allelopathic substances of the submerged macrophyte stratiotes aloides’, *International Review of Hydrobiology*. John Wiley & Sons, Ltd, 95(3), pp. 224–234. doi: 10.1002/iroh.200911219.

Mulderij, G. *et al.* (2007) ‘Allelopathic activity of Stratiotes aloides on phytoplankton—towards identification of allelopathic substances’, *Hydrobiologia*. Dordrecht: Springer Netherlands, 584, pp. 89–100. doi: 10.1007/s10750-007-0602-0.

Nakai, S., Zou, G., Okuda, T., Tsai, T.-Y., Song, X., Nishijima, W., Okada, M. (2010) ‘Anti-cyanobacterial allelopathic effects of plants used for artificial floating islands’, *Allelopathy Journal*, 1, pp. 113–121.

Nakai, S. *et al.* (1999) ‘Growth inhibition of blue–green algae by allelopathic effects of macrophytes’, *Water Science and Technology*. No longer published by Elsevier, 39(8), pp. 47–53. doi: 10.1016/S0273-1223(99)00185-7.

Nakai, S., Yamada, S. and Hosomi, M. (2005) ‘Anti-cyanobacterial fatty acids released from Myriophyllum spicatum’, *Hydrobiologia*. Kluwer Academic Publishers, 543(1), pp. 71–78. doi: 10.1007/s10750-004-6822-7.

Pakdel, F. M. *et al.* (2013) ‘Allelopathic inhibition of microalgae by the freshwater stonewort, chara australis, and a submerged angiosperm, potamogeton crispus’, *Aquatic Botany*. Elsevier B.V., 110, pp. 24–30. doi: 10.1016/j.aquabot.2013.04.005.

Rojo, C., Segura, M. and Rodrigo, M. A. (2013) ‘The allelopathic capacity of submerged macrophytes shapes the microalgal assemblages from a recently restored coastal wetland’, *Ecological Engineering*. Elsevier, 58, pp. 149–155. doi: 10.1016/j.ecoleng.2013.06.019.

Saito, K. *et al.* (1989) ‘Inhibitory Substances from Myriophyllum brasiliense on Growth of Blue-Green Algae’, *Journal of Natural Products*. American Chemical Society, 52(6), pp. 1221–1226. doi: 10.1021/np50066a004.

Takeda, F. *et al.* (2011) ‘Allelopathic Potential of Potamogeton pusillus Community Against Microcystis aeruginosa’, *Journal of Water and Environment Technology*. Japan Society on Water Environment, 9(1), pp. 21–28. doi: 10.2965/jwet.2011.21.

Wang, L.X., Zhang, L., Zhang, Y.X., Jin, C.Y., Lu, C.M., Wu, G. . (2006) ‘The inhibitory effect of Hydrilla verticillata culture water on Microcystic aeruginosa and its mechanism’, *Journal of Plant Physiology and Molecular Biology*, 32(6), pp. 672–678.

Wu, X. *et al.* (2012) ‘Allelopathic Effects of Eicchornia Crassipes Growth of Microcystis aeruginosa’, *Journal of Agricultural Science and Technology*, 2, pp. 1400–1406. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-84893752045&origin=inward (Accessed: 18 February 2019).

Wu, X. *et al.* (2013) ‘Effects of allelochemical extracted from water lettuce (Pistia stratiotes Linn.) on the growth, microcystin production and release of Microcystis aeruginosa’, *Environmental Science and Pollution Research*. Springer Berlin Heidelberg, 20(11), pp. 8192–8201. doi: 10.1007/s11356-013-1783-x.

Xian, Q. *et al.* (2006) ‘Isolation and identification of antialgal compounds from the leaves of Vallisneria spiralis L. by activity-guided fractionation’, *Environmental Science and Pollution Research*. Ecomed, 13(4), pp. 233–237. doi: 10.1065/espr2006.06.314.

Y. Gao, B.Liu, D.Xu, Q. Zhou, C. Hu, F. Ge, L. Zhang, Z. W. (2011) ‘Phenolic compounds exuded from two submerged freshwater macrophytes and their allelopathic effects on microcystis aeruginosa’, *Polish Journal of Environmental Studies*, 20(5), pp. 1153–1159.

Zhang, S.H., Cheng, S.P., Wang, H.Q., He, F., Wu, Z. . (2009) ‘Allelopathic interactions between the potamogeton spp and toxic cyanobacteria (Microcystis aeruginosa)’, *Allelopathy Journal*, 23(2), pp. 379–390.

Zhang, S. (2015) ‘Allelopathic Activities of Three Emergent Macrophytes on Several Monospecific Cyanobacterial Species and Natural Phytoplankton Assemblages’, *Polish Journal of Environmental Studies*. HARD Publishing s.c. Jerzy Radecki, Hanna Radecka, 24(1), pp. 397–402. doi: 10.15244/pjoes/26972.

Zhang, Sheng hua, Zhang, Shi yang and Li, G. (2016) ‘Acorus calamus root extracts to control harmful cyanobacteria blooms’, *Ecological Engineering*, 94, pp. 95–101. doi: 10.1016/j.ecoleng.2016.05.053.

Zhang, T. *et al.* (2012) ‘Inhibitory Effects and Mechanisms of Hydrilla verticillata (Linn.f.) Royle Extracts on Freshwater Algae’, *Bull Environ Contam Toxicol*, 88, pp. 477–481. doi: 10.1007/s00128-011-0500-z.

Zhang, T. T. *et al.* (2011) ‘Growth inhibition and biochemical changes of cyanobacteria induced by emergent macrophyte Thalia dealbata roots’, *Biochemical Systematics and Ecology*. Pergamon, 39(2), pp. 88–94. doi: 10.1016/j.bse.2011.01.004.

Zhang, T. T., Hu, W. and Zhang, D. (2011) ‘Allelopathic Effect of Typha angustifolia L. on Phytoplankton’, *Advanced Materials Research*, 383–390, pp. 3724–3728. doi: 10.4028/www.scientific.net/AMR.383-390.3724.

Zhou, S. *et al.* (2004) ‘Inhibition of Cyanobacterial Growth by Allelopathy of Reed’, *Japanese Journal of Water Treatment Biology*, 40(1), pp. 23–28. doi: 10.2521/jswtb.40.23.

Zhu, J. *et al.* (2010) ‘Study on the mechanism of allelopathic influence on cyanobacteria and chlorophytes by submerged macrophyte (Myriophyllum spicatum) and its secretion’, *Aquatic Toxicology*. Elsevier B.V., 98(2), pp. 196–203. doi: 10.1016/j.aquatox.2010.02.011.

Złoch, I. *et al.* (2018) ‘Allelopathic effects of Chara species (C. aspera, C. baltica, and C. canescens) on the bloom-forming picocyanobacterium Synechococcus sp.’, *Environmental Science and Pollution Research*. Springer Berlin Heidelberg, 25(36), pp. 36403–36411. doi: 10.1007/s11356-018-3579-5.

Zuo, S. *et al.* (2016) ‘Antialgal effects of five individual allelochemicals and their mixtures in low level pollution conditions’, *Environmental Science and Pollution Research*. Environmental Science and Pollution Research, 23(15), pp. 15703–15711. doi: 10.1007/s11356-016-6770-6.