

Neurochemical Pollutants in Aquatic Ecosystems: Modes of Interaction with Microalgae

Boyang Cao^{1,2}, O. B. Chivkunova², T. A. Fedorenko²,
A. E. Solovchenko², E. S. Lobakova², A. V. Oleskin²

¹ MSU-BIT University, Shenzhen, China

² Biology Department, Lomonosov Moscow State University, Russian Federation

Our previous publication in “Life on the Earth” [7] was concerned with neuroactive substances in the capacity of new-generation pollutants exemplified by neurotransmitters such as acetylcholine and biogenic amines. At low concentrations, these substances exert a growth-promoting effect on microalgae. The present work deals with the mode of action of extremely low concentrations (“trace amounts”) of neurotransmitters that comprises their antioxidant effects and the influence on the dynamics and rhythms of microalgal cultures’ development, i.e. on the succession of their age-related stages. Such neurotransmitters that can enter natural ecosystems with the wastewater of food, drug, and cosmetic industry, can be grouped into (1) substances that increase the unsaturated fatty acid (UFA) content in microalgal membranes, elevate the photosynthetic pigment concentration in the cells, and prolong the “youth” of microalgal cultures; and (2) substances that decrease the UFA content, reduce the photosynthetic pigment concentration, and, accordingly, accelerate the “aging” of microalgal cultures.

Keywords: ecotoxicants, neurotransmitters, serotonin, histamine, norepinephrine, dopamine, acetylcholine, microalgae, developmental stages of microalgal cultures.

Abbreviations: 5-HT, serotonin; ACh, acetylcholine; BA, biogenic amine; DA, dopamine; FA, fatty acid; NE, norepinephrine; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; QS, quorum sensing; SFA, saturated fatty acid; UFA, unsaturated fatty acid.

For citation: Cao, B., Chivkunova, O.B., Fedorenko, T.A., Solovchenko, A.E., Lobakova, E.S., Oleskin, A.V., “Neurochemical Pollutants in Aquatic Ecosystems: Mode of Interaction with Microalgae”, *Zhizn Zemli* [Life of the Earth] **48**, no 1, 46–57 (2026) (in Engl., abstr. inRuss.). DOI: 10.29003/m5046.0514-7468.2026_48_1/46-57.

Нейрохимические загрязнители в водных экосистемах: механизмы взаимодействия с микроводорослями

Боян Цао, О.Б. Чивкунова, Т.А. Федоренко, А.Е. Соловченко,
Е.С. Лобакова, А.В. Олескин*

В предшествующей статье в журнале «Жизнь Земли» [7] были рассмотрены нейрорактивные вещества как загрязнители нового поколения – на примерах ней-

* Цао Боян – аспирант, кафедра общей экологии и гидробиологии, биологический факультет МГУ имени М.В. Ломоносова и МГУ-ППИ (Шэньчжэнь, Китай), caobh@my.msu.ru, ORCID 0009-0003-5068-8536; Чивкунова Ольга Борисовна – к.б.н., с.н.с., кафедра биоинженерии, биологический факультет МГУ имени М.В. Ломоносова, ORCID 0000-0002-1625-4510; Федоренко Татьяна Александровна – к.б.н., с.н.с., кафедра биоинженерии, биологический факультет МГУ; Соловченко Алексей Евгеньевич – д.б.н., проф., кафедра биоинженерии, биологический факультет МГУ, ORCID 0000-0001-6746-8511; Лобакова Елена Сергеевна – д.б.н., проф., кафедра биоинженерии, биологический факультет МГУ; Олескин Александр Владимирович – д.б.н., проф., кафедра общей экологии и гидробиологии, биологический факультет МГУ имени М.В. Ломоносова, oleskin@yandex.ru, ORCID 0000-0002-6816-1615.

ротрансмиттеров, таких как ацетилхолин и биогенные амины. Данные вещества при низких концентрациях вызывают стимуляторные ростовые эффекты у микроводорослей. В настоящей статье обсуждаются механизмы действия нейротрансмиттеров даже в «следовых» количествах, а именно, антиоксидантное действие и влияние на динамику и ритмику развития микроводорослей – на смену их «возрастных» стадий. Испытанные нейротрансмиттеры, которые могут поступать в природные экосистемы со стоками пищевой, фармацевтической и косметической индустрии, можно подразделить на две подгруппы: 1) вещества, которые увеличивают содержание ненасыщенных жирных кислот (НЖК) в мембранах микроводорослей, повышают концентрацию фотосинтетических пигментов в клетках и, предположительно, продлевают ранние стадии культуры микроводорослей, и 2) вещества, снижающие содержание НЖК в мембранных липидах, уменьшающие концентрацию фотосинтетических пигментов и, соответственно, ускоряющие достижение поздних стадий культуры.

Ключевые слова: экотоксиканты, нейротрансмиттеры, серотонин, гистамин, норадреналин, дофамин, ацетилхолин, микроводоросли, возрастные стадии культур микроводорослей.

Ссылка для цитирования: Цао Боян, Чивкунова О.Б., Соловченко А.Е., Лобаква Е.С., Олескин А.В. Нейрохимические поллютанты в водных экосистемах: механизмы взаимодействия с микроводорослями // Жизнь Земли. 2026. Т. 48, № 1. С. 46–57. DOI: 10.29003/m5046.0514-7468.2026_48_1/46-57.

Поступила 21.11.2025 / Принята к публикации 04.03.2026

Introduction. Among numerous human-produced “gifts” recently given to the Earth’s biosphere, significant importance should currently be placed on neuroactive pollutants that were considered by us in the previous publication [7]. It was emphasized that these chemicals produce significant effects on natural ecosystems even when present at extremely low concentrations (as trace amounts). This may be due to the fact that the pollutants are recognized by ecosystem components as their own regulatory or signal substances. The issue to raise is what the mode of neuroactive pollutants’ action on ecosystems is like.

Stimulatory effects of neurotransmitters. In this work and in Ref. [7]), it was revealed that low (micromolar) concentrations of the neurotransmitters acetylcholine (ACh), serotonin (5-HT), histamine, dopamine (DA), and norepinephrine (NE) promote the growth of green microalgae (domain Viridiplantae, phylum Chlorophyta) belonging to several taxonomic groups, such as *Chlorella vulgaris* (class Trebouxiophyceae), *Scenedesmus quadricauda* (class Chlorophyceae, order Sphaeroleales), *Haematococcus lacustris* (class Chlorophyceae, order Chlamydomonadales), as well as of a prokaryote, the cyanobacterium *Limnospira platensis* (kingdom/domain Bacteria, phylum Cyanobacteria, class Cyanophyceae, order Oscillatoriales). These data were presented in the authors’ published work [8–10, 16, 17].

The growth of the microalgal cultures was estimated from the number of cells per 1 mL of the culture volume. Our experiments provided evidence that all tested neurotransmitters increase the cell number of the culture of the green microalgae *Scenedesmus quadricauda* (widely used as a carotenoid producer in cosmetics and drug preparations). As for another popular microalga, chlorella (*Chlorella vulgaris*), dopamine and norepinephrine only accelerated its growth without increasing the final biomass yield, whereas other tested neurotransmitters elevated the biomass yield, i.e. functioned as true growth stimulants (see the previous work in Zhizn’ Zemli: [7]). These effects were produced by neurotransmitter concentrations of 1 and/or 10 micromol/L (μM) but not by their higher concentrations (e.g., 100 μM).

Our data concerning another phytoplankton representative, the cyanobacterium *Limnospira platensis* also known as “Spirulina” (Fig. 1) can be briefly summed up as follows



Fig. 1. Trichomes (cell chains) of *L. platensis* (“Spirulina”).
Рис. 1. Трихомы (цепи клеток) *L. platensis* («Спирulina»).

[10]. In the control culture (without the addition of neurotransmitters), the dry weight (upon dehydration) per 1 cm³ increased during the cultivation of “Spirulina” and reached the maximum level (a plateau) by day 14. Among the tested neurotransmitters, ACh, histamine, and 5-HT increased, and DA decreased the culture biomass on day of cultivation; these effects tapered off by day 14.

In summary, DA slowed down the growth and biomass accumulation in the cyanobacterium, whereas the other neurotransmitters sped up these processes. From the environmental viewpoint, the challenge is that the growth-stimulating neurotransmitters entering natural ecosystems with the wastewater of pharmaceutical industry may cause microalgal blooming in water bodies, consuming dissolved oxygen and resulting in their eutrophication as pointed out in our previous work [7].

At this point, the issue concerning the possible mode of action of neurotransmitters should be revisited. The question to address is why substances known to transmit impulses in the nervous system can accelerate the growth of microalgae and/or promote biomass accumulation by them?

Unfortunately, only a limited number of publications on neurotransmitter effects on microalgae are available in the literature [12, 18, 22, 23, 29, 31]. However, there are data on the influence of phytohormones on microalgae [19, 21, 30, 32] including cyanobacteria [27]. Phytohormones are chemically and functionally similar to neurotransmitters. Low concentrations of various phytohormones (auxins, gibberellins, cytokinins, brassinosteroids, ethylene, and abscisic, salicylic, and jasmonic acid) exert a stimulatory influence on microalgal growth, the biosynthesis of valuable biotechnological products, and stress resistance [5, 6, 21].

In the literature, several mechanisms of the stimulatory effects of phytohormones on microalgae are suggested; they will be discussed in separate subsections, and the applicability of these suggestions to neurotransmitters will be considered.

Antioxidant activity that depends on the activation of enzymes that quench reactive oxygen species and on an increase in the concentrations of antioxidants such as ascorbic acid and glutathione. For instance, it was demonstrated that the auxins indole-3-acetic acid,

indole-3-butyric acid, and phenylacetic acid, as well as their synthetic analog 1-naphthaleneacetic acid stimulated *C. vulgaris* growth at concentrations of 0.1–1.0 μM . These effects were attributed to the activation of antioxidant systems by these hormones since they were revealed to increase ascorbate peroxidase, catalase, and superoxide dismutase activities and to decrease lipid peroxidation and H_2O_2 accumulation [19]. Since serotonin and some other neurotransmitters are capable of quenching reactive oxygen species and preventing the peroxidation of unsaturated fatty acids in lipids, it is likely that antioxidant activity contributes to their stimulatory action on the content of biomass, photosynthetic pigments, and fatty acids (see below). However, this explanation seems to be insufficient to account for the observed effects of low neurotransmitter concentrations.

Promotion of photosynthetic activity by increasing the photosynthetic pigment content, which, in turn, implies an increase in gene expression that is related to chlorophyll and carotenoid synthesis. Auxins are known to cause an increase in photosynthetic pigment production in the aforementioned experiments [19]. The data on an increase in photosynthetic pigment content in the presence of neurotransmitters (see [7]) are consistent with this suggestion. However, the impact of phytohormones and chemically related neurotransmitters on the photosynthetic apparatus apparently forms a part of a more general effect considered in the following subsection of this work.

Influence of neurotransmitters on the dynamics and rhythms of development of microalgal cultures. Phytohormones are known to exert a regulatory influence on biorhythms and the dynamics of undergoing “age-related” stages in the development of plants. For instance, abscisic acid and ethylene promote leaf shedding, suppress growth processes, and accelerate plant senescence [5, 6]. There are analogous examples concerning microalgae. Of note is a study that dealt with serotonin and its derivative melatonin. In the cells of the charophyte *Chara australis*, diurnal oscillations in serotonin and melatonin concentrations were revealed, and the oscillation rhythm was different under long day (12 hs light:12 hs dark) and short day (9 hs light:15 hs dark) conditions [29].

In the literature on microalgae (reviewed, [29]), including the author’s published work [8], the suggestion was put forward that neurotransmitters decelerate the growth stages of batch cultures, prolonging the earlier stages with active protosynthesis and cell proliferation. In terms of this suggestion, it is possible to account for the drop in trichome number on day 7 of cultivation and continued trichome proliferation up to day 14 on which the trichome number clearly tends to decrease in the control culture.

Impact of neurotransmitters on the fatty-acid composition of microalgae. In connection with the effects of neurotransmitters on the dynamics of the development of microalgal cultures, research on the influence of neurotransmitters on the fatty-acid composition in microalgae seems to be of considerable interest. It is known that active growing “young” cultures are characterized by more unsaturated fatty acids in their lipids, whereas the “older” cultures predominantly contain saturated fatty acids (SFAs). The following is to sum up the Ph. D. thesis data obtained using gas chromatography with mass spectrometry [8–10].

The data obtained on the contents of various fatty acid species in *C. vulgaris*, *S. quadricauda*, *H. lacustris*, and *L. platensis* reveal a sophisticated pattern that reflects the specific features of each neurotransmitter and each of the microalgae. The present work only deals with the influence of neurotransmitters on the ratio between saturated and unsaturated fatty acids (SFAs and UFAs, respectively); UFAs are subdivided into mono- and polyunsaturated fatty acids, i.e., MUFAs and PUFAs, respectively. The trends singled out in *C. vulgaris* and *S. quadricauda* (Table 1) are as follows:

(1) ACh and histamine increased the percentage of unsaturated and decreased that of saturated fatty acids in the lipids of the microalgae under study.

(2) DA and 5-HT decreased the percentage of unsaturated fatty acids (MUFAs and PUFAs) in *S. quadricauda*. In *C. vulgaris*, the effects of DA and 5-HT on the PUFA content were not statistically verifiable.

(3) NE exerted no significant effect on the two tested microalgal species.

Table 1. Summarized data on the impact of BAs on the fatty acid composition of the lipids of the tested microalgae. Designations: ↗, upward trends; ↘, downward trends; —, insignificant or ambiguous effects. IPPAS H-239 and BM-1, *H. lacustris* strains

Таблица 1. Обобщённые данные по влиянию БА на жирнокислотный состав липидов у тестируемых микроводорослей, тенденции: ↗, увеличение параметра; ↘, уменьшение параметра; —, эффект незначительный или неоднозначный. IPPASH-239 и BM-1, штаммы *H. Lacustris*

Characteristics	Species/strain of microalgae	Biogenic amines				
		5-HT	His	DA	NE	ACh
1	2	3	4	5	6	7
Total fatty acid content, mg/g of dry biomass	<i>C. vulgaris</i>	↘	↘	↗	↗	↗
	<i>S. quadricauda</i>	↘	↗	↘	—	↗
	IPPAS H-239	—	↗	↘	↗	↗
	BM-1	↘	↗	↘	↗	↗
	<i>L. platensis</i>	↗*	—	—	↘	↗
Percentage of unsaturated fatty acids	<i>C. vulgaris</i>	—	↗	—	—	↗
	<i>S. quadricauda</i>	↘	↗	↘	—	↗
	IPPAS H-239	—	—	—	↗	—
	BM-1	—	—	↗	↗	—
	<i>L. platensis</i>	↗**	↘	—	↗**	—
Percentage of saturated fatty acids	<i>C. vulgaris</i>	↘	↘	—	—	↘
	<i>S. quadricauda</i>	↗	↘	↗	—	↘
	IPPAS H-239	—	—	—	↘	—
	BM-1	—	—	↘	↘	—
	<i>L. platensis</i>	—	—	—	—	—

* at a concentration of 0.1 μM only; ** only the PUFA fraction with a decrease in MUFA fraction.

* только в концентрации 0.1 мкМ; ** только фракция ПНЖК со снижением доли МНЖК.

As for the cyanobacterium *L. platensis*, 5-HT and NE significantly increased the PUFA share; the other neurotransmitters produced no statistically valid effects.

The effects of neurotransmitters on the green microalga *Haematococcus lacustris* (strains IPPAS H-239 and BM-1) are presented in more detail here below. The data in the **Tables 2-6** are based on the published work [9] and illustrate our data concerning strain BM-1 (isolated from the brackish water of the White Sea [11]).

As shown in the Tables above, ACh (see Table 2) and histamine (Table 3) increased, and DA (Table 4) the total fatty acid content in the lipids of the microalgal cells. Despite its chemical similarity to DA, NE, nevertheless, increased the total fatty acid content (table 5) in *H. lacustris*.

Table 2. Fatty acid content of *H. lacustris* BM-1 cultures grown with or without serotonin (5-HT). Averaged values based on the results of 4-5 repeats are given here and below. Kruskal-Wallis test results with independent samples for the experimental and control groups. SFAs: Sig.=0.035 < 0.05. MUFAs: Sig.=0.025 < 0.05. PUFAs: Sig.=0.047 < 0.05 Total fatty acid content: Sig.=0.026 < 0.05. The results for all the groups rule the null hypothesis out, indicating significant differences between the data groups to be compared

Таблица 2. Содержание жирных кислот (ЖК) в клетках *H. lacustris* BM-1, культивируемых с серотонином (5-НТ) или без него. Даны усреднённые значения по результатам 4–5 повторностей. Результаты Н-теста Крускала-Уоллиса с независимыми выборками для экспериментальных и контрольной групп: НЖК: Sig.=0.035 < 0.05. МНЖК: Sig.=0.025 < 0.05. ПНЖК: Sig.=0.047 < 0.05. Суммарное содержание ЖК: Sig.=0.026 < 0.05. Результаты не соответствуют нулевой гипотезе, что свидетельствует о значимых различиях между экспериментальными и контрольными данными

Fatty acid	Proportion in total fatty acids. %			
	Control	5-НТ, 0.1мк	5-НТ, 1 мк	5-НТ, 10мк
Saturated fatty acids (SFAs)	33.9 ± 1.5	36.8 ± 1.6	34.6 ± 1.4	33.3 ± 1.1
Monounsaturated fatty acids (MUFAs)	25.2±1.1	23.3 ± 1.2	25.1 ± 1.1	23.0 ± 1.0
Polyunsaturated fatty acids (PUFAs)	41.0 ± 1.7	39.9 ± 1.1	40.3± 1.66	43.6 ± 1.9
Total fatty acid content, mg/g of dry biomass (on day 14 of cultivation) here and in T.3-6	86.7±2.0	73.1±2.0	85.4±1.0	76.9±2.0

Table 3. Fatty acid (FA) content of *H. lacustris* BM-1 cultures grown with or without histamine (His). Kruskal-Wallis test results with independent samples for the experimental and control groups. SFAs: Sig.=0.108 > 0.05. MUFAs Sig.=0.043 < 0.05. PUFAs: Sig.= 0.05. FA content: Sig.=0.016 < 0.05. The results for the SFA group are not significant

Таблица 3. Содержание ЖК в клетках *H. lacustris* BM-1, культивируемых с гистамином (Гис) или без него. Результаты Н-теста Крускала-Уоллиса с независимыми выборками для экспериментальных и контрольной групп: НЖК: Sig.=0.108 > 0.05. МНЖК: Sig.=0.043 < 0.05. ПНЖК: Sig.=0.05. Суммарное содержание ЖК: Sig.=0.016 < 0.05. Результаты свидетельствуют о значимых различиях между сравниваемыми данными, кроме данных НЖК

Fatty acid	Proportion in total fatty acids. %			
	Control	His, 0.1 мк	His, 1 мк	His, 10 мк
Saturated fatty acids (SFAs)	38.9±2.0	36.9±1.8	35.8±2.0	35.0±1.9
Monounsaturated fatty acids (MUFAs)	25.3±1.4	24.4±1.5	23.6±1.3	23.7±1.4
Polyunsaturated fatty acids (PUFAs)	35.8±1.9	38.7±1.8	40.6±2.0	41.4±2.1
Total fatty acid content, mg/g	70.2±2.0	141.4±2.0	155.5±2.0	58.4±2.0

As for the impact on the ratio between fatty acid types in *H. lacustris*, NE shifted the ratio in favor of PUFAs. DA increased the PUFA percentage only in one of the tested strains, BM-1. Ach, 5-HT, and histamine failed to exert any statistically significant influence on the ratio between SFAs and UFAs in the lipids of *H. lacustris*.

Impact of neurotransmitters on culture development stages (age-related processes) in microalgae. Batch cultures like those used in this work are known to undergo several development stages [14], including the lag, exponential, growth deceleration, and stationary phase. Academician Nikolai Yerusalimsky, an eminent Russian microbiologist, compared

the development stages of microbial cultures to the phases of the life-cycle of multicellular organisms. In his classical work, he underscored the adaptive role of the culture development stage succession, involving the stepwise transition from the actively proliferating “young” to the resting “aged” culture: “The existence in the resting or inactive state followed by the proliferation outburst enabled by contacting a nutrient pool and, thereupon, by the reversion to the inactive state – these are the habitual stages of the bacterial life-cycle under natural conditions” [2] (quoted according to Ref. [1]).

Table 4. Fatty acid content of *H. lacustris* BM-1 cultures grown with or without dopamine (DA). Kruskal--Wallis test results with independent samples for the experimental and control groups. SFAs: Sig.=0.031 < 0.05. MUFAs: Sig.=0.294 > 0.05. PUFAs: Sig.=0.036 < 0.05 Total FA content: Sig.=0.023 < 0.05. The differences between the control and experimental data for MUFAs are not significant

Таблица 4. Содержание ЖК в клетках *H. lacustris* BM-1, культивируемых с дофамином (ДА) или без него. Результаты Н-теста Крускала-Уоллиса с независимыми выборками для экспериментальных и контрольной групп: НЖК: Sig.=0.031 < 0.05. МНЖК: Sig.=0.294 > 0.05. ПНЖК: Sig.=0.036 < 0.05. Суммарное содержание ЖК: Sig.=0.023 < 0.05. Результаты свидетельствуют о значимых различиях между экспериментальными и контрольными данными, кроме данных по МНЖК

Fatty acid	Proportion in total fatty acids. %			
	Control	DA, 0.1 мμ	DA, 1 мμ	DA, 10 мμ
Saturated fatty acids (SFAs)	37.41 ± 1.2	35.17 ± 1.2	34.51 ± 1.2	40.01 ± 1.3
Monounsaturated fatty acids (MUFAs)	26.1 ± 1.3	23.31 ± 1.9	24.45 ± 2.3	23.83 ± 1.8
Polyunsaturated fatty acids (PUFAs)	36.4 ± 1.3	41.5 ± 1.4	41.02 ± 1.3	35.91 ± 1.6
Total fatty acid content, mg/g	62.5 ± 2.0	54.8 ± 2.0	57.5±2.0	51.6 ± 2.0

Table 5. Fatty acid content of *H. lacustris* BM-1 cultures grown with or without norepinephrine (NE). Kruskal-Wallis test results with independent samples for the experimental and control groups. SFAs: Sig.=0.016 < 0.05. MUFAs: Sig.=0.764 > 0.05. PUFAs: Sig.=0.048 < 0.05 Total FA content: Sig.=0.023 < 0.05. The differences between the control and experimental data for MUFAs are not significant

Таблица 5. Содержание ЖК в клетках *H. lacustris* BM-1, культивируемых с нордреналином (НА) или без него. Результаты Н-теста Крускала-Уоллиса с независимыми выборками для экспериментальных и контрольной групп: НЖК: Sig.=0.016 < 0.05. МНЖК: Sig.=0.764 > 0.05. ПНЖК: Sig.=0.048 < 0.05. Суммарное содержание ЖК: Sig.=0.023 < 0.05. Результаты свидетельствуют о значимых различиях между экспериментальными и контрольными данными, кроме данных по МНЖК

Fatty acid	Proportion in total fatty acids. %			
	Control	NE, 0.1 мμ	NE, 1 мμ	NE, 10 мμ
Saturated fatty acids (SFAs)	34.0±1.0	32.8 ± 1.8	32.6 ± 1.7	31.6 ± 1.1
Monounsaturated fatty acids (MUFAs)	23.0±1.6	21.9 ± 1.8	22.2 ± 1.6	22.4 ± 1.6
Polyunsaturated fatty acids (PUFAs)	43.0±1.1	45.3 ± 1.4	45.2 ± 1.6	46.0 ± 1.0
Total fatty acid content, mg/g	87.0±3.0	83.6±3.0	91.5±3.0	97.9±3.0

Table 6. Fatty acid content of *H. lacustris* BM-1 cultures grown with or without acetylcholine (ACh). Kruskal-Wallis test results with independent samples for the experimental and control groups. SFAs: Sig.=0.789 > 0.05. MUFAs: Sig.=0.764 > 0.05. PUFAs: Sig.=0.016 < 0.05 Total FA content: Sig.=0.016 < 0.05. The differences between the experimental and control data groups for SFAs and MUFAs are not significant

Таблица 6. Содержание ЖК в клетках *H. lacustris* BM-1, культивируемых с ацетилхолином (АХ) или без него. Результаты Н-теста Крускала-Уоллиса с независимыми выборками для экспериментальных и контрольной групп: НЖК: Sig.=0.789 > 0.05. МНЖК: Sig.=0.764 > 0.05. ПНЖК: Sig.=0.016 < 0.05. Суммарное содержание ЖК: Sig.=0.016 < 0.05. Результаты свидетельствуют о значимых различиях между экспериментальными и контрольными данными, кроме данных для НЖК и МНЖК

Fatty acid	Proportion in total fatty acids. %			
	Control	ACh, 0.1 мμ	ACh, 1 мμ	ACh, 10 мμ
Saturated fatty acids (SFAs)	35.7±1.9	35.1±2.0	35.6±2.1	36.1±1.8
Monounsaturated fatty acids (MUFAs)	23.6±1.3	23.3±1.5	22.5±1.5	22.2±1.4
Polyunsaturated fatty acids (PUFAs)	40.7±2.1	41.5±2.0	41.9±2.1	41.7±1.9
Total fatty acid content, mg/g	70.6±2.0	57.9±2.0	81.3±2.0	98.0±2.0

The ground-breaking work carried out by Yerusalimsky and other researchers was followed by numerous studies on the developmental dynamics of diverse microorganisms. Suffice it to mention the research on the development stage succession in lacto- and bifidobacteria that are utilized in dairy industry; Russian researchers revealed not only exponential but also linear growth stages in the development dynamics of their cultures [3].

The capacity of microorganisms including microalgae to transition from stage to stage in the quasi-aging process can be considered to form a part of the more general strategy of biological systems known as allostasis. "Allostasis... is about adapting to changes in the internal and external environment with the goal of surviving even when faced with uncertain circumstances, balancing internal parameters essential for life with the changing world around us" [25]. The specific mechanisms and stages of the senescence of microbial cultures remain highly debatable in the present-day literature. In particular, a controversial issue is whether microbial senescence is an internally preprogrammed process or depends, to a certain extent, on environmental conditions including stress factors [26].

In light of the data obtained, it seems likely that ACh, histamine, and, to limited extent, NE in the tested eukaryotic microalgae (and ACh and 5-HT in the cyanobacterium) actually prolong the early cultivation stages (the culture's "youth") that are characterized by rapid cell division and the expansion of photosynthetic membranes (thylakoids in eukaryotes) that contain PUFA-enriched lipids.

Presumably, the unicellular photosynthetic pro- and eukaryotes investigated in the present work express receptors for neurotransmitters. Similar to mammalian receptor-based systems for recognizing neurotransmitters, the cAMP messenger system may modulate the activity of desaturases involved in producing PUFAs, so as to maximize their yield [20].

A different mode of action seems to be characteristic of the second neurotransmitter subgroup including 5-HT and DA that tend to decrease the PUFA percentage in favor of saturated or monounsaturated fatty acids. If microalgal cells contain mammal-type receptors (or their analogs) they might downregulate fatty acid desaturases and/or inhibit their activity,

resulting in accelerated algal culture development and an increased share of saturated reserve triacylglycerides

In the literature, there are analogous studies on the quasi-aging dynamics of various microalgae in batch cultures. For instance, the culture of the green microalga *Pseudokirchneriella subcapitata* undergoes at least three distinguishable stages of development: (i) the first 3–4 days of cultivation are characterized by a rapid (exponential) growth of the culture; the cells contain large chloroplasts and are green in color, due to a high chlorophyll content; (ii) between day 5 and 12 of cultivation, the cells lose the green color; their division is arrested, and the chloroplasts shrink; (iii) after day 12, the cells become yellow; their membranes lose their integrity, and cell death is observed [15].

Impact of neurotransmitters on the photosynthetic pigment content. The aforementioned classification of neurotransmitters based on their effects on the fatty-acid composition of microalgal lipids is apparently consistent with the data on their influence on microalgal pigments that were expounded in the previous work [7]. For instance, ACh and histamine that increase the unsaturated fatty acid percentage in both *S. quadricauda* and *C. vulgaris*, also elevate the chlorophyll *a* and carotenoid content and plausibly promote photosynthetic activity; this is characteristic of the early development stages of microalgal cultures whose “youth” is extended by these neurotransmitters. Conversely, DA that increases the saturated fatty acid percentage in the lipid fraction (and accelerates the culture’s “aging”) also decreases the photosynthetic pigment content, albeit it in *S. quadricauda* only.

As pointed out above, the effects of 5-HT and NE on the fatty-acid content seem to indicate that they also extend the early stages of development of the *L. platensis* culture. At least, the influence of 5-HT on the photosynthetic pigments resulting in an increase in their content is quite consistent with the suggestion that 5-HT “prolongs the youth” of *L. platensis* (“Spirulina”), which involves photosynthesis intensification and the prevalence of unsaturated fatty acids.

To re-emphasize, the microalga *H. lacustris* is characterized by its own quasi-aging dynamics in batch culture that includes the transition from the green vegetative (chlorophyll-accumulating) stage via the intermediate brown palmelloid stage combining chlorophylls and carotenoids to the red encysted (carotenoid-enriched) stage. As we pointed out in the previous work [7]: among the neurotransmitters tested in the present work, NE and ACh stimulated the synthesis of both chlorophylls and carotenoids in the two strains of *H. lacustris* on day 7 and 14 of cultivation; histamine and DA promoted these processes in strain BM-1 only. In distinction from BM-1, Histamine, 5-HT, and DA decreased the chlorophyll and carotenoid content of strain IPPAS H-239.

The results presented in this work seem to be somewhat paradoxical in light of the literature data on the competition between (1) the synthesis of chlorophyll forming a part of the photosystems and (2) the formation of secondary carotenoids, especially astaxanthin, in *H. lacustris* (reviewed, [24]). However, are these two processes inevitably antagonistic (according to the *zero-sum* principle)?

The data obtained can be interpreted in terms of available information on the intermediate developmental stage (the middle-aged culture) that combines chlorophyll and carotenoid production. Such a culture chiefly contains non-motile palmelloid cells featuring a sizeable amount of astaxanthin against the background of a significant chlorophyll content [24].

As mentioned above, palmelloid cell numbers significantly increased in the presence of NE and, in strain IPPAS B-239, also of ACh. Presumably, ACh and NE in both tested strains

as well as histamine and DA in strain BM-1 lock the culture's development at the palmelloid stage. Therefore, the hypothetic mode of action of neurotransmitters is based on regulating the carotenoid and chlorophyll synthesis pathways so as to achieve an equilibrium between them and maintain sufficiently high concentrations of both pigment types.

On the contrary, such neurotransmitters as 5-HT in strain IPPAS H-239 presumably prevent the cultures from staying in the palmelloid stage, which can account for the neurotransmitters' inhibitory effects on both carotenoid and chlorophyll synthesis.

Conclusion. To sum up our experimental data, neurotransmitters that can enter natural ecosystems with the wastewater of food, drug, and cosmetic industry, can be grouped into (1) substances that increase the unsaturated fatty acid (UFA) content in microalgal membranes, elevate the photosynthetic pigment concentration in the cells, and prolong the "youth" of microalgal cultures and (2) substances that decrease the UFA content, reduce the photosynthetic pigment concentration, and, accordingly, accelerate the "aging" of microalgal cultures. The neurotransmitters hypothetically intervene with the quasi-aging dynamics of microalgal cultures, either prolonging the earlier stages with a high photosynthetic pigment content and the prevalence of UFAs in the lipids or, alternatively, accelerating the transition to the later stages with a lowered photosynthetic pigment content and the dominance of SFAs. If such neurotransmitters spread in water bodies, with the wastewater of pharmaceutical, food, or cosmetic industry, then negative consequences are to be expected at the ecosystem level for both options (microalgal culture "rejuvenation" or "premature aging").

The increase in photosynthetic pigment content associated with the "rejuvenation" scenario (and plausibly causing photosynthesis intensification) poses the threat of uncontrollable proliferation of microalgae and water body eutrophication.

The "aging" of microalgal cultures that entails a decrease in photosynthetic pigment content can result in reducing their productivity in the capacity of the main organic substance producers within the phytoplankton and, accordingly, disrupt the functioning of natural aquatic ecosystems.

The issue to be resolved is how neurotransmitter that decrease photosynthetic pigment content and plausibly reduce photosynthetic activity can stimulate/accelerate the growth of microalgal cultures (see the beginning of this work and [7]). The suggestion to be made in this context is that microalgae can efficiently grow without active photosynthesis by consuming organic substance contained in the medium, i.e. by transitioning from the phototrophic to the heterotrophic lifestyle. Therefore, we surmise that the operation of the whole aquatic ecosystem can be disrupted because *microalgae as the main producers* switch to utilizing organic substances and therefore, start functioning as *consumers*.

From the biotechnological viewpoint, both the early stage-prolonging and the late stage onset-accelerating neurotransmitters have some potential, especially as both subgroups can promote the growth of microalgal cultures. The former subgroup (ACh, histamine, 5-HT, and NE (in *H. lacustris*)) of neurotransmitters holds some promise with regard to producing PUFA-enriched preparations for therapeutic or cosmetic purposes [13, 28]. The latter subgroup of neurotransmitters (DA and 5-HT in *S. quadricauda* and *C. vulgaris*) are potentially applicable for practical developments aimed at producing biofuel. Saturated and monounsaturated fatty acid-containing triacylglycerides hold special promise in terms of producing biodiesel [4]).

Our two recent papers on neurotransmitters as new-generation pollutants produced for *Zhizn' Zemli* [Life of the Earth] enable us to draw the conclusion that these chemicals pose a threat in environmental terms at very low concentrations because they are recognized by natu-

ral ecosystem components as analogs of their own, endogenous, regulatory substances and signals. The neurotransmitters' mode of action is likely to involve several mechanisms including antioxidant activity and, still more important in ecological terms, effects on the developmental dynamics of microalgal cultures within the framework of the phytoplankton of water ecosystems. This may result in seriously disrupting the functioning of aquatic ecosystems, posing the threat of the eutrophication of natural or artificial (aquacultural) water bodies.

Funding. This research was partly funded by the Development Program of the Interdisciplinary Scientific and Educational School of Lomonosov Moscow State University named "The Future of the Planet and Global Environmental Change", as well as by the Shenzhen Municipal Government and Shenzhen MSU-BIT University. The fatty acid profiling was funded by the Russian Science Foundation (grant 23-74-00037).

References

1. Golovlev, E.L., "Academician N.D. Yerusalimsky", *Microbiology (Moscow)* **68**(6), 800–808 (in Russian).
2. Yerusalimsky, N.D., *Physiology of Development of Pure Cultures. Dr. Sci. Biol. Thesis* (Moscow: Institute of Microbiology of the USSR Academy of Sciences, 1952) (in Russian).
3. Maryin, V.A., Kharitonov, D.V., "Study on the sequence of growth phases in the batch cultures of bifidobacteria or lactobacteria", *Technique and Technology* **19**(4) (2010) (in Russian).
4. Feofilova, E.P., Mysiakina, I.S., *Biofuel: problems and prospects* (Moscow: National Academy of Mycology, 2016) (in Russian).
5. Tsavkelova, E.A., Klimova, S.Yu., Cherdynitseva, T.A., Netrusov, A.I., "Microorganisms producing plant growth stimulants: practical applications (a review)", *Appl. Biochem. Microbiol.* **42**(2), 133–143 (2006) (in Russian).
6. Tsavkelova, E.A., Klimova, S.Yu., Cherdynitseva, T.A., Netrusov, A.I., "Hormones and hormone-like compounds of microorganisms (a review)", *Appl. Biochem. Microbiol.* **42**(3), 261–268 (2006) (in Russian).
7. Cao, B., Oleskin, A.V., "Neurochemical pollutants in the aquatic medium: the results of studies with model organisms (microalgae)", *Zhizn Zemli [Life on the Earth]* **47**(4), 26–40 (2025). DOI: 10.29003/m28.0514-7468.
8. Cao, B., Chivkunova, O.B., Solovchenko, A.E., Lobakova, E.S., Oleskin, A.V., "Impact of neurotransmitters on the fatty acid composition and pigments of the green microalga *Scenedesmus quadricauda*", *Appl. Biochem. Microbiol.* **60**(5), 833–843 (2024). DOI: 10.1134/S0003683824604554.
9. Cao, B., Fedorenko, T.A., Chivkunova, O.B., Solovchenko, A.E., Lobakova, E.S., Oleskin, A.V., "Impact of neurotransmitters on the photosynthetic pigment content of the green microalga *Haematococcus lacustris* (strains IPPAS H-239 and BM-1)", *Appl. Biochem. Microbiol.* **61**(5), 865–871 (2025). DOI: 10.1134/S0003683825601155.
10. Cao, B., Fedorenko, T.A., Chivkunova, O.B., Solovchenko, A.E., Lobakova, E.S., Oleskin, A.V., "Impact of neurotransmitters on biomass accumulation, photosynthetic pigment content, and fatty acid composition of the cyanobacterium *Limnospira platensis* IPPAS B-256", *Microbiology (Moscow)* **95** (1), 82-95 (2026). DOI: 10.1134/S0026261725602921.
11. Chekanov, K., Lobakova, E., Selyakh, I., Semenova, L., Sidorov, R., Solovchenko, A., "Accumulation of astaxanthin by a new *Haematococcus pluvialis* strain BM1 from the White Sea coastal rocks (Russia)", *Mar Drugs*. **12**(8), 4504–4520 (2014). DOI: 10.3390/md12084504.
12. Czerpak, R., Bajguz, A., Jewiec, P., Muszynska-Garstka, M., "The influence of acetylcholine and taurine on the content of some metabolites in the alga *Chlorella vulgaris*", *Ecohydrol. Hydrobiol.* **3**(2), 223–229 (2003).
13. Fabris, M., Abbriano, R.M., Pernice, M., Sutherland, D.L., Commault, A.S., Hall, C.C., Labbeuw, L., McCauley, J.I., Kuzhiuparambil, U., Ray, P., Kahlke, T., Ralph, P.J., "Emerging technologies in algal biotechnology: toward the establishment of a sustainable, algae-based bioeconomy", *Front. Plant Sci.* **11**, 279 (2020). DOI: 10.3389/fpls.2020N/D279.
14. Love, A.C., Trivisano, M., "Microbes modelling ontogeny", *Biol. Philos.* **28**, 161–188 (2013). DOI: 10.1007/s10539-013-9363-5.

15. Machado, M., Soares, E.C.S., "Life and death of *Pseudokirchneriella subcapitata*: physiological changes during chronological aging", *Appl. Microbiol. Biotechnol.* **1066**, 8245–8258 (2022). DOI: 10.1007/s00253-022-12267-5.
16. Oleskin, A.V., Postnov, A.L., Boyang, C., "Impact of biogenic amines on the growth of a *Chlorella vulgaris* culture", *J. Pharm. Nutr. Sci.* **11**, 49–53 (2021). DOI: 10.29169/1927-5951.2021.11.07.
17. Oleskin, A.V., Postnov, A.L., Boyang, C., "Impact of biogenic amines on the growth of green microalgae", *J. Pharm. Nutr. Sci.* **11**, 144–150 (2021). DOI:10.29169/1927-5951.2021.11.17.
18. Parsaiemehr, A., Sun, Z., Dou, X., Chen, Y.-F., "Simultaneous improvement in production of microalgal biodiesel and high-value alpha-linolenic acid by a single regulator acetylcholine", *Biotechnol. Biofuels.* **8**, 11 (2015). DOI: 10.1186/s13068-015-0196-0.
19. Piotrowska-Niczyporuk, A., Bajguz, A., "The effect of natural and synthetic auxins on the growth, metabolite content and antioxidant response of the green alga *Chlorella vulgaris* (Trebouxio-phyceae)", *Plant Growth Regul.* **73**, 57–66 (2014). DOI: 10.1007/s10725-013-9867-7.
20. Powell, K., *Pharm: The Comprehensive Pharmacology Reference* (Amsterdam: Elsevier, 2007. P. 1–2).
21. Qiu, J., Vadiveloo, A., Mao, B.-D., Zhou, J.-L., Gao, T., "Phytohormones as a novel strategy for promoting phytoremediation in microalgae: progress and prospects", *J. Environ. Management.* **273**, 123593 (2025).
22. Roshchina, V.V., Yashin, V.A., Podunai, Y.A., "Fluorescence in the study of diatom *Ulnaria ulna* cells", *Austin Environ. Sci.* **7** (3), 107–110 (2022).
23. Schiechl, G., Himmelsbach, M., Buchberger, W., Kerschbaum, H.H., Lütz-Meindl, U., "Identification of acetylcholine and impact of cholinomimetic drugs on cell differentiation and growth in the unicellular green alga *Micrasterias denticulate*", *Plant Sci.* **175**(3), 262–266 (2008). DOI: 10.1016/j.plantsci.2008.04.006.
24. Solovchenko, A., "Recent breakthroughs in the biology of astaxanthin accumulation by microalgal cells", *Photosynthesis Res.* **125**(3), 437–449 (2015). DOI: 10.1007/s11120-015-0156-3.
25. Steffen, P.R., Hedes, D., Matheson, R., "The brain is adaptive not triune: how the brain responds to threat, challenge, and change", *Front. Psychiatr.* **13**, 802606 (2022). DOI: 10.3389/fpsy.2022.802606.
26. Steiner, U.K., "Senescence in bacteria and its underlying mechanisms", *Front. Cell Dev. Biol.* **9**, 668915 (2021). DOI: 10.3389/fcell.2021.668915.
27. Tiwari, S., Patel, A., Prasad, S.M., "Phytohormone upregulates the biochemical constituent, exopolysaccharide and energy metabolism in paddy-field cyanobacteria exposed to chromium stress", *BMC Microbiol.* **20**, 206 (2020). DOI: 10.1186/s12866-020-01799-3.
28. Tredici, M.R., Rodolfi, L., Biondi, N., Bassi, N., Sampietro, G., "Techno-economic analysis of microalgal biomass production in a 1-ha Green Wall Panel (GWP*) plant", *Algal Res.* **19**, 253–263 (2016). DOI: 10.1016/j.algal.2016.09.005.
29. Van Alstyne, K.L., Ridgway, R.L., Nelson, A., "Neurotransmitters in marine and freshwater algae", *Neurotransmitters in Plants: Perspectives and Applications* (Boca Raton (FL): CRC Press, 2018), 27–36. DOI: 10.1201/b22467-3.
30. Yu, J., You, X., Gao, Y., Guo, L., Xang, X., Gao, M., Zhao, Y., Jin, C., Ji, J., Che, Z., "The impact of auxin analogs on microalgal intracellular component accumulation and nutrient removal for mariculture wastewater treatment basing on bacterial-algal coupling technology", *Process Safety and Environmental Protection* **164**, 660–668 (2022).
31. Zhao, Y., Li, Q., Yang, M., Huang, F., Liu, J., Yu, X., Yu, L., "Exploiting synergy of dopamine and stressful conditions in enhancing *Haematococcus lacustris* biomass and astaxanthin yield", *Biore-source Technol.* **417**, 131848 (2025). DOI: 10.1016/j.biotech.2024.131848.
32. Zhao, C., Lu, B., Wang, Z., Wei, J., Zhao, Y., Wang, S., "Enhanced antibiotics and antibiotics resistance genes removal from aquaculture wastewater by microalgae-based system induced with plant hormones", *Int. Biodeterior. Biodegrad.* **200**, 106045 (2025). DOI: 10.1016/j.ibiod.2025.106045.