ISSN 0026-2617, Microbiology, 2006, Vol. 75, No. 4, pp. 374–379. © Pleiades Publishing, Inc., 2006.
Original Russian Text © A.V. Oleskin, T.A. Kirovskaya, 2006, published in Mikrobiologiya, 2006, Vol. 75, No. 4, pp. 440–445.

CONFERENCE PROCEEDINGS

Research on Population Organization and Communication in Microorganisms

A. V. Oleskin[1] and T. A. Kirovskaya

Sector for Biosocial Studies, Department of Microbial Physiology, Faculty of Biology, Moscow State University, Moscow 119992, Russia

Received February 27, 2006; revised March 6, 2006

Abstract—This review concentrates on the history of the subfield of microbiology referred to as the population organization- and communication-related research direction (POCRRD). The focal points of POCRRD include intercellular interactions, information exchange between cells, and multicellular structures (colonies, biofilms, flocs, etc.). Special attention in this review is given to the contribution of Russian scientists to the development of POCRRD. In terms of POCRRD, microorganisms are viewed as social creatures that constantly communicate and form supraorganismic, intrinsically heterogeneous systems.

DOI: 10.1134/S0026261706040023

Key words: microbial population, communication, autoregulators, biogenic amines, colony architecture, social behavior

This work deals with the history of the *population organization- and communication-related research direction* (POCRRD) in microbiology and sums up its conceptual basis. POCRRD places special emphasis on population structures (colonies, biofilms, cell aggregates, and flocs), on the functional specialization of microbial cells (the functional heterogeneity of populations), and on the mechanisms of information exchange between cells in these structures. Although most microbiologists believe that POCRRD was initiated and developed by scientists outside of Russia, the development of this research direction was actually antedated by Russian publications that have not yet received sufficient attention from specialists in the history of science [1].

1. Setting the Historical Stage for the Development of POCRRD

At the turn of the 20th century, the ideas of the biosphere as a coherent whole, a "thin film of life" (E. Suss and V.I. Vernadsky), and of the flora of the planet Earth as a continuous system (L.G. Ramensky) were put forward. It was suggested that evolution results from the formation of symbiotic systems involving several organisms (A.S. Famintsyn, B.M. Kozo-Polyansky, etc.), and parallels between human society and groups of animals (A. Espinas and P.A. Kropotkin) and even of plants (the "phytosociology" school in botany) were drawn. For instance, G.F. Morozov regarded a forest as a "complex organism" and a "social entity" [2]. Pioneering works on ecology (e.g., those published by E. Haeckel) and Spencer's philosophical theory, which holds that the social structures formed by humans derive from those of animals, attracted the attention of researchers to the study of interactions between living organisms.

Of particular importance for the development of POCRRD was research on *microbial ecology*, which dates back to the beginning of the 20th century. The early studies in this field focused on the global biogeochemical role of microorganisms viewed as constituents of natural ecosystems and of the biosphere as a whole (works by S.N. Winogradsky, V.L. Omeliansky, M. Beijerinck, etc.). Although the works of microbial ecologists predominantly dealt with *interspecies interactions* in microorganisms, a large number of studies (conducted by D.M. Novogrudsky, N.G. Cholodny, and N.A. Krasil'nikov, among others) were also concerned with processes carried out by single-species populations.

Of considerable interest were studies of the chemical factors produced by microorganisms that influence the development of their cultures. These factors are referred to as autoregulators. In the early 20th century, O. Rahn [3] and W. Penfold [4] revealed that substances triggering the onset of the exponential growth phase accumulate in the culture fluid during the lag phase. This system was analyzed in more detail in the studies of pro- and eukaryotic microorganisms over the course of more than 50 years (overviewed in G.I. El'-Registan's dissertation [5]).

---

[1] Corresponding author; e-mail: AOleskin@rambler.ru

It was N.D. Ierusalimsky who succeeded in carrying out the challenging task of theoretically generalizing the knowledge accumulated in this field, although the contributions of other scientists (N.A. Krasil'nikov, V.F. Perfil'ev, etc.) should also be recognized. In 1946–1949, Ierusalimsky [6–8] developed his concept of a bacterial culture as a coherent, organism-like system; this concept was formulated in his dissertation [9] in which the following systemic properties were emphasized:

1. The phenotypic heterogeneity of microbial cultures, which manifests itself in the coexistence of different (geno)types in bacterial populations that have to adapt to various conditions. This phenomenon was described by Ierusalimsky in terms of "adaptive modification."

2. A culture's capacity to release chemical factors modulating its development and to assess its own density according to the concentrations of these factors (foreshadowing the quorum sensing concept developed in the West only in the 1990s—see the review by I.A. Khmel in this issue 10]).

3. A unitary developmental cycle (ontogeny). Ierusalimsky was convinced that a "bacterial culture as a whole undergoes a sequence of certain age-dependent changes, an ontogeny" [11, p. 8].

4. Close relationship between a culture's development and environmental factors: "in order to understand the driving forces of the ontogeny of a bacterial culture, we should take into account that it develops as a coherent system involving cells and environmental conditions" [9, p. 157].

2. *Main POCRRD Subfields*

The POCRRD aspects in which significant progress was made during the second half of the 20th century are:

Research on the heterogeneity of microbial populations and on the polymorphism of microbial cells. This POCRRD subfield dates back to N.F. Gamaleya's work (1894) [12]. Using LiCl, he obtained various morphological variants of bacterial cells he termed "heteromorphic forms." In 1920, R. Legroux and J. Magrou [13] revealed differences among the cells of a *Vibrio cholerae* colony. During the 1930s and 1940s, a school of medical microbiologists formed in Russia (M.A. Peshkov, V.D. Timakov, etc.) renowned for their works on L forms of pathogenic bacteria, i.e., forms whose cell wall is defective or lacking (reviewed in monograph [14]). This research paralleled analogous studies conducted abroad [15, 16]. During the second half of the 20th century, researchers succeeded in elucidating various stages of L transformation and describing L forms differing in their morphology and in the degree of completeness and irreversibility of L transformation. Of relevance to this subject are, among others, the works of V.V. Vysotsky et al. [17–19]. Research was carried out on the formation of phenotypically distinct dissociants (phase dissociants) in microorganisms (see, e.g., [20–22]) whose cells differ in thickness and chemical composition of the cell envelope, growth and metabolite excretion rate, cell resistance to external factors, and the morphology of cells and whole colonies. The studies conducted at the Department of Microbial Physiology of the Biology Faculty of Moscow State University beginning in the late 1970s (see [23–25] and other articles) concentrated on the generation of L forms in cyanobacteria. Since 1983, studies on the heteromorphism of cyanobacteria associated with cells of higher plants (tobacco, nightshade, etc. [26–28]) have been in progress.

Studies conducted by S.G. Smirnov [29–31] at the Ivanovo State Institute of Medicine revealed that microbial populations consist of a number of distinct "cell clusters" including the following: (i) cell clusters that differ in growth and division rate; (ii) clusters of actively dividing, dormant, and spontaneously autolyzing cells; and (iii) cell clusters with different surface potential values. Additional variants of cell clusters (as denoted by Smirnov) were detected in subsequent studies. For example, a microbial biofilm can include two cell clusters, one composed of surface-attached cells and the other of buoyant, "planktonic," cells [32, 33].

Research on chemical communication factors. In the late 1960s, A.S. Khokhlov et al. detected an A factor (subsequently identified as 3S-isocapryloyl-4S-hydroxymethyl-γ-butyrolactone [34, 35]) in populations of the actinomycete *Streptomyces griseus.* This factor induced streptomycin synthesis and spore formation in *S. griseus* mutants or disscociants that lacked these activities. In the early 1980s, further research on this subject was carried out by a team of Japanese scientists who described the mechanism of operation of the A factor inactivating the repressor of the genes involved in streptomycin synthesis [36, 37]. Since the early 1970s, a research team at the Institute of Microbiology, Russian Academy of Sciences (G.I. El'-Registan, V.I. Duda, V.A. Svetlichnyi, etc.) has investigated microbial autoregulatory factors (reviewed in [38]). They have characterized the self-regulatory systems that are based on factors d_1 (alkylhydroxybenzenes, AHB) functioning as anabiosis autoinducers, and d_2 (unsaturated fatty acids) serving as autolysis autoinducers ([39, 40] and other publications). In the 1970s, P.A. Pshenichnov and his associates from the Institute of Ecology of the Urals Division of the USSR Academy of Sciences published their first articles on the autometabolic regulation of the developmental cycle of an *E. coli* population, paying special attention to the substances that inhibit or stimulate its development [41–43]. The role of autoregulatory factors in *E. coli* populations was also investigated in a series of works by T.Ya. Vakhitov at the Institute of Superpure Preparations in St. Petersburg [44, 45]. In the 1970s, the research teams of J. Hastings and A. Thomas obtained data on the substances produced by marine luminescent bacteria and pneumococci that induce luminescence and transformation competence, respectively, provided their concentrations are sufficiently high. An integrated concept concerning the operation of communication systems that sense cell density (quorum sensing systems, see review in this issue [10]) was developed in the 1990s.

The authors of this review made their own contribution to this area of experimental research by investigating the regulatory effects of biogenic amines in microbial systems. We established that serotonin stimulates growth, cell aggregation, and extracellular matrix formation in *E. coli* and *Rhodospirillum rubrum*, and promotes cyst formation in the myxobacteria *Polyangium sp.* Its high concentrations suppress membrane potential generation [46, 47]. Subsequently, we demonstrated growth stimulation by dopamine and norepinephrine in *E. coli* and in the yeast *Saccharomyces cerevisiae* Dopamine and serotonin, but not norepinephrine, stimulated the respiratory activity of *E. coli* cells; all three tested amines stimulated yeast respiration [48]. Using high performance liquid chromatography, we detected serotonin in the biomass of bacteria *Bacillus subtilis* and *Staphylococcus aureus*, norepinephrine in *B. subtilis*, *B. cereus*, *Proteus vulgaris*, and *Serratia marcescens*, and dopamine in a majority of the tested prokaryotes [49].

Research on physical communication factors. In the 1920s, the radiation from living cells stimulating the division of other cells was detected by A.G. Gurvich's research team. L.B. Severtsova [50] established that the radiation emitted by yeasts of the genus *Nadsonia* (the donor) enhances the cell density of irradiated cultures of bacteria of the genus *Bacillus* (the acceptor). The works of a number of Russian scientists, e.g., A.Kh. Tambiev and his associates, deal with the effects of millimeter radio waves on growth, colony structure, and enzyme biosynthesis in microorganisms (these data were generalized in the monograph [51]). In 1990, Yu.A. Nikolaev revealed [52] that a *Vibrio costicola* culture emits a signal that stimulates the growth of another culture separated by a quartz glass layer. Subsequently, analogous data were obtained by a team of Japanese microbiologists [53]. Presumably, ultrasound waves are involved in transmitting the signals. Chemical and physical communication factors seem to produce synergistic effects (see review [54]).

Research on social behaviors of microorganisms. In 1972, S.G. Smirnov introduced the concepts of *ethology*, the science dealing with animal behavior, into microbiology. He defined bacterial ethology as *the theory concerned with behavioral patterns of prokaryotes on the cell and population levels.* [31, 55]. Over the course of the last decades, ethological concepts were applied to bacteria in works by A.V. Oleskin [56, 57], J. Shapiro [58], and P. Corning [59]. Of particular interest are the data concerning the coordination of cell behaviors on the population-wide scale, including collective aggression, the isolation of populations from one another, and cooperation. Cell cooperation enables a colony to move as a coherent entity on the substrate surface, as shown by K.N. Sherstobaev (1961) who investigated bacilli [60]. Coordinated movements of cells in a colony were investigated in detail in studies with myxobacteria (see review, [58]).

Research on colony architecture. Studies concerning colony organization were initiated in the 1970–1980s. For example, A.P. Puzyr' and O.A. Mogil'naya [61, 62] used electron microscopy to demonstrate the spatial orderliness of a bacterial colony as a coherent system comprising several ultrastructurally different cell layers. Starting from the mid-1980s, E.O. Budrene investigated the formation of structural patterns in bacterial colonies growing on an agar-containing medium [63, 64]. I.V. Botvinko [65, 66] argued that the extracellular biopolymer matrix performs structure-stabilizing and protective functions in a colony or biofilm. Signal molecules can diffuse in a hydrophilic matrix. J. Shapiro in his classical article “Bacteria as multicellular organisms” [58] considered the myxobacterium *Myxococcus xanthus* growing on a solid medium as a model system. Its starving cells form aggregates (fruiting bodies). Cells therein include the lysing and myxospore-forming subpopulations. Similar morphogenetic processes were revealed, e.g., in *B. subtilis*. On an agarized medium, its colony forms arboreal structures and thereafter films that cover the whole agar surface and contain fruiting bodylike formations [67]. *E. coli* K-12 biofilms form ordered periodic structures; it has been suggested that their formation results from the combined effects of poly-β-1,6-*N*-acetyl-*D*-glucosamine that causes cell adhesion and a hypothetical adhesion autoinhibitor [33]. Studies concerning bacterial adhesins and antiadhesins are in progress at the Institute of Microbiology of the Russian Academy of Sciences [54].

Over the course of the 20th century, research on population organization and communication in microorganisms placed particular emphasis on the **relationships between microbial populations and macroorganisms in the ecosystems** to which they belonged. Microorganisms release signal molecules while interacting with macroorganisms (in the context of symbiotic or parasite–host relationships) or with other microorganisms within the framework of an ecosystem. Evidence is mounting that macroorganisms exert their influence on autoregulatory processes in microorganisms. For instance, the L-canavanine produced by alfalfa plants inhibits quorum sensing systems responsible for exopolysaccaride II and violaceine synthesis by the bacterial symbiont *Sinorhizobium melitoti* [68].

3. An “Interim Report” on the Progress of POCRRD and Its Prospects for the Future

Taken together, the studies conducted in the research area under study convey the message that a microbial population consists of cells that differ in their properties and functions. They can use chemical and physical (contact and, presumably, distant) communication channels. The communication systems provide for the integrity of the population, despite its lack of a central control agency, enabling microbial cells to display various social behaviors from aggression to cooperation. As a coherent system, a microbial population forms supracellular structures (exemplified by matrix). It is characterized by a unitary ontogeny (as originally termed by N.D. Ierusalimsky). A population is adapted to its life within the framework of an ecosystem and the biosphere as a whole.

POCRRD is related to the *biosocial paradigm* in biology that concentrates on supraorganismic (biosocial) systems ranging from coelenterate colonies to insect societies and ape groups. This paradigm also applies to humankind (biopolitics, see [56]). POCRRD is of considerable practical (clinical and biotechnological) importance. Interestingly, the formation of ordered structures such as biofilms by pathogens enhances their resistance to the host immune system and to antibiotics [69]. Population heterogeneity that manifests itself, e.g., in growth rate differences among microbial cells, makes it possible for a biotechnologist to efficiently select for strains of interest during continuous cultivation [70].

REFERENCES

1. Kirovskaya, T.A., Research on Microbial Population Organization and Intercellular Communication in the USSR (Russia) in the Second Half of the 20th Century, *Cand. Sci. (Biol.) Dissertation*, Moscow: Institute of History of Science and Technology, 2005.
2. Morozov, G.F., *Science of Forestry*, St. Petersburg, 1912.
3. Rahn, O., Über Den Einfluß der Stoffwechselprodukte auf das Wachstum der Bakterien, *Zbl. Bakteriol. Parasitenk*, 1906, vol. 16, pp. 417–429.
4. Penfold, W.J., On the Nature of the Bacterial Lag, *J. Hygiene*, 1914, vol. 14, pp. 215–241.
5. El'-Registan, G.I., Role of membranotropic Autoregulatory Factors in the Processes of Microbial Growth and Development, *Doctoral (Biol.) Dissertation*, Moscow: Institute of Microbiology, USSR Academy of Sciences, 1989.
6. Ierusalimsky, N.D., On the Physiological Stages of Development of Bacteria, *Mikrobiologiya*, 1946, vol. 15, pp. 405–416.
7. Ierusalimsky, N.D., *Azotnoe i vitaminnoe pitanie mikrobov* (Nitrogen and Vitamin Nutrition of Microorganisms), Moscow: Akad. Nauk SSSR, 1949.
8. Ierusalimsky, N.D., The Problem of Bacterial Ontogenesis and the Ways of its Solving, *Trudy Instituta Mikrobiologii AN SSSR*, 1951, vol. 1, pp. 5–43.
9. Ierusalimsky, N.D., Physiology of Development of Pure Bacterial Cultures, *Doctoral (Biol.) Dissertation*, Moscow: Institut mikrobiologii AN SSSR, 1952.
10. Khmel, I.A., Quorum-Sensing Regulation of Gene Expression: Fundamental and Applied Aspects and the Role in Bacterial Communication, *Mikrobiologiya*, 2006, vol. 75, no. 4.
11. Ierusalimsky, N.D., Physiology of Development of Pure Bacterial Cultures, *Extended Abstract of Doctoral (Biol.) Dissertation*, Institute of Microbiology, USSR Academy of Sciences, 1952.
12. Gamaleya, N.F., Heterotrophic Bacteria under the Influence of Lithium Salts, *Vrach*, 1894, no. 20.
13. Legroux, R. and Magrou, J., Etat organisé des colonies bacteriennes, *Ann. Inst. Pasteur*, 1920, vol. 34, pp. 417–431.
14. Prozorovskii, S.V., Kats, L.N., and Kagan, G.Ya., *L-formy bakterii* (L-Forms of Bacteria), Moscow: Meditsina, 1981.
15. Kleinberger-Nobel, E., The Natural Occurrence of Pleuropneumonia-Like Organisms, Their Apparent Symbiosis with *Streptobacillus moniliformis* and Other Bacteria, *J. Pathol. Bacteriol*, 1935, vol. 40, pp. 93–105.
16. Dienes, L. and Weinberger, L., *The L-forms of bacteria, Bacteriol. Rev*, 1951, vol. 15, pp. 245–288.
17. Vysotskii, V.V., Ultrastructure of Brucellas. Report 1: Ulstrastructure of the S cells, *Zhurn. Mikrobiol*, 1965, vol. 11, pp. 3–6.
18. Vysotskii, V.V. and Androsov, V.V., Characteristics of the Cellular Ultrastructure in the Intact Population of some S. typhimurium and *E. coli* strains, *Zhurn. Mikrobiol. Epidemnaya. Immunobiol*, 1976, no. 12, pp. 32–37.
19. Vysotskii, V.V., Zaslavskaya, P.L., Mashkova, A.V., and Baulina, O.I., Polymorphism as a Rule in Development of Prokaryotic Populations, *Biologicheskie Nauki*, 1991, no. 12, pp. 5–17.
20. Zharikova, G.G., Makarova, G.Ya., Poglazova, M.N., and Zarubina, A.P., Colony Formation and Development in Dissociated forms of *Bacillus brevis* G-B, *Mikrobiologiya*, 1966, vol. 35, no. 4, pp. 647–650.
21. Milko, E.S., Sperlup, O.W., and Rabotnova, I.L., Die Milchsäuregärung von *Lactobacterium delbruckii* bei Kontinuierlicher Kultivierung, *Z. Allg. Mikrobiol*, 1966, vol. 6, no. 4, pp. 297–301.
22. Mil'ko, E.S. and Egorov, N.S., *Geterogennost' populyatsii bakterii i protsess dissotsiatsii* (Heterogeneity of Bacterial Populations and the Process of Dissociation), Moscow: Mosk. Gos. Univ., 1991.
23. Baulina, O.I., Semenova, L.R., Mineeva, L.A., and Gusev, M.V., The Ultrastructural Organization in the Cells of Heterotrophic Blue-Green Alga *Chlorogloea fritschii, Mikrobiologiya*, 1978, vol. 47, no. 5, pp. 919–925.
24. Gusev, M.V., Baulina, O.I., Semenova, L.R., and Mineeva, L.A., Ultrastructure of Lysozyme-Induced and Spontaneously Formed Cyanobacteria *Chlorogloea fritschii* with Cell Wall Deficiency, *Mikrobiologiya*, 1982, vol. 51, no. 4, pp. 622–627.
25. Gusev, M.V., Baulina, O.I., Semenova, L.R., Mineeva, L.A., and Kats, L.N., Electron Microscopic Study of L-Like Colonies of *Chlorogloea fritschii* Cyanobacteriai, *Mikrobiologiya*, 1983, vol. 52, no. 4, pp. 629–633.
26. Baulina, O.I., Agafodorova, M.N., Korzhenevskaya, T.G., Gusev, M.V., and Butenko, R.G., Cyanobacteria in an Artificial Association with Tobacco Callus Tissue, *Mikrobiologiya*, 1984, vol. 53, no. 6, pp. 997–1002.

27. Baulina, O.I. and Lobakova, E.S., Atypical Cell Forms Overproducing Extracellular Substances in Populations of Cycad Cyanobionts, *Mikrobiologiya*, 2003, vol. 72, no. 6, pp. 792–805 [*Microbiology* (Engl. Transl.), 2003, vol. 72, no. 6, pp. 701–712].

28. Gorelova, O.A., Communication of Cyanobacteria with Plant Partners During Association Formation, *Mikrobiologiya*, 2006, vol. 75, no. 4 [*Microbiology* (Engl. Transl.), 2006, vol.75, no. 4].

29. Smirnov, K.K. and Smirnov, S.G., Some Aspects of Measurement of the Physicochemical Parameters of Developing Pathogenic Bacteria, in *Fiziko-khimicheskie issledovaniya patogennykh enterobakterii v protsesse kul'tivirovaniya* (Physicochemical Research on Pathogenic Enterobacteria During Cultivation), Ivanovo: Ivanovskii gosudarstvennyi meditsinskii institut, 1974.

30. Smirnov, S.G., The Problem of Choice of Substantial Parameters for Systemic Study of Bacterial Batch Cultures, in *Fiziko-khimicheskie issledovaniya patogennykh enterobakterii v protsesse kul'tivirovaniya* (Physicochemical Research on Pathogenic Enterobacteria During Cultivation), Ivanovo: Ivanovskii gosudarstvennyi meditsinskii institut, 1979, pp. 13–24.

31. Smirnov, S.G., *Etologiya bakterii* (Ethology of Bacteria), Ivanovo: Ivanovskaya gosudarstvennaya meditsinskaya akademiya, 2004.

32. Stoodley, P., Sauer, K., Davies, D.G., and Costerton, J.W., Biofilms As Complex Differentiated Communities, *Annu. Rev. Microbiol.*, 2002, vol. 56, pp. 187–209.

33. Agladze, K., Wang, X., and Romeo, T., Spatial Periodicity of *Escherichia coli* K-12 Biofilm Microstructure Initiates During a Reversible, Polar Attachment Phase of Development and Requires the Polysaccharide Adhesion PGA, *J. Bacteriol.*, 2005, vol. 187, no. 24, pp. 8237–8246.

34. Khokhlov, A.S., Anisova, L.S., and Tovarova, I.I., Effect of A-Factor on the Growth of Asporogenic Mutants of *Streptomyces griseus, Z. Allg. Mikrobiol*, 1973, vol. 13, pp. 647–655.

35. Kornitskaya, E.Ya., Tovarova, I.I., Soifer, V.S., and Khokhlov, A.S., Research on the Regulation of Streptomycin Biosynthesis Using a Blocked Mutant of *Actinomyces streptomycini, Antibiotiki*, 1976, vol. 21, no. 1, pp. 10–14.

36. Hara, O.T. and Beppu, T., Mutants Blocked in Streptomycin Production in *Streptomyces griseus*–the Role of the A-Factor, *J. Antibiot.*, 1982, vol. 35, pp. 349–358.

37. Miyake, K., Kuzuyama, T., Horinouchi, S., and Beppu, T., The A-Factor-Binding Protein of *Streptomyces griseus* Negatively Controls Streptomycin Production and Sporulation, *J. Bacteriol.*, 1990, vol. 172, no. 6, pp. 3003–3009.

38. Bukharin, O.V., Gintsburg, A.L., Romanova, Yu.M., El'-Registan, G.I. *Mekhanizmy vyzhivaniya bakterii* (Mechanisms of Bacterial Survival), Moscow: Meditsyna, p. 367.

39. Kaprel'yants, A.S., El'-Registan, G.I., Kozlova, A.N., Mityushina, L.L., Duzha, M.V., Poplaukhina, O.G., Duda, V.I., Ostrovskii, D.I., and Ignatov, S.G., Changes of Metabolism and Ultrastructural Organization of *Bacillus cereus* Cells under the Influence of the Specific Autoregulatory Factor, *Eksperimental'noe izuchenie razvitiya mikroorganizmov* (Experimental Study of Microbial Development), Pariiskaya, A.I., Ed., Pushchino-na-Oke: USSR Acad. Sci. NTsBI, 1978, pp. 24–25.

40. Duda, V.I., Pronin, S.V., El'-Registan, G.I., Kaprel'yants, A.S., and Mityushin, L.L., Formation of Refractive Resting Cells in *Bacillus cereus* under the Influence of an Autoregulatory Factor, *Mikrobiologiya*, 1982, vol. 51, no. 1, pp. 77–81.

41. Pshenichnov, R.A., Kolotov, V.M., Korobov, V.P., Barikhin, S.Ya., Sokolova, N.A., Ivakina, A.M., and Tkachenko, A.G., On the Existence of Specific Factors Controlling the Development of Microbial Populations. First Observations on Revealing the Factor Limiting Biomass Accumulation in *Escherichia coli* M-17 Cultures, *Ekologiya*, 1973, no. 3, pp. 5–13.

42. Pshenichnov, R.A., Kolotov, V.M., Barikhin, S.Ya., Tkachenko, A.G., and Dedyukina, M.M., Microbial Culture as an Autoregulated System, *Ekologiya i populyatsionnaya genetika mikroorganizmov*, (Ecology and Population Genetics of Microorganisms), Shvarts, S.S., Ed., Sverdlovsk: Ural'skii nauchnyi tsentr AN SSSR, 1975.

43. Pshenichnov, R.A., Tkachenko, A.G., and Zelenin, E.N., Effect of Extracellular Autometabolites on the Ecological Coefficient of *Escherichia coli* populations of Different Density, *Ekologiya*, 1981, no. 1, pp. 93–95.

44. Vakhitov, T.Ya., Aleksin, L.M., and Osokova, L.I., Role of Intrapopulation Factors at the Stage of *Escherichia coli* Death, *Tez. IV Vses. konf. "Upravlyaemoe kul'tivirovanie mikroorganizmov"* (Tses. IV Ull-Union Conf. "Controlled Cultivation of Microorganisms"), Pushchino, 1986, pp. 55-56.

45. Vakhitov, T.Ya., Protasov, E.A., Visnol'd, N.V., Tolparov, Yu.N., and Petrov, L.N., Isolation and Identification of *Escherichia coli* Growth Autostimulators, *Zhurn. Mikrobiol. Epidemiol. Immunobiol*, 2003, no. 2, pp. 7–12.

46. Oleskin, A.V., Kirovskaya, T.A., Botvinko, I.V., and Lysak, L.V., Effects of Serotonin (5-Hydroxytryptamine) on the Growth and Differentiation of Microorganisms, *Mikrobiologiya*, 1998, vol. 67, no. 3, pp. 305–312 [*Microbiology* (Engl. Transl.), 1998, vol. 67, no. 3, pp. 251–257].

47. Kirovskaya, T.A., Effects of Serotonin on the Physiology and Colonial Organization of Microorganisms, in *EURESCO Conference "Bacterial Neural Networks (Intracellular Signalling)"*. Book of Abstracts, Holland, B., et al., Eds., Obernai (France), 2002, p. 48.

48. Kagarlitskii, G.O., Kirovskaya, T.A., and Oleskin, A.V., Effect of Neuromediator Amines on Microbial Growth and Respiration, *Biopolitika. Otkrytyi mezhdistsiplinarnyi seminar na biologicheskom fakul'tete Moskovskogo gosudarstvennogo universiteta im. M.V. Lomonosova* (Biopolitics. An Open Interdisciplinary Seminar in the Biological Faculty of M.V. Lomonosov Moscow State University), M.: Mosk. Gos. Univ., 2003, pp. 13–17.

49. Tsavkelova, E.A., Botvinko, I.V., Kudrin, V.S., and Oleskin, A.V., Detection of Neuromediator Amines in Microorganisms by High-Performance Liquid Chromatography, *Dokl. Akad. Nauk*, 2000, vol. 372, pp. 840–842.

50. Sewertzowa, L.B., Über den Einfluß der mitogenetischen Strahlen auf die Vermehrung der Bacterien, *Biol. Zentralbl.*, 1929, vol. 49, pp. 212–225.

51. Tambiev, A.Kh., Kirikova, N.N., Betskii, O.V., and Gulyaev, Yu.V., *Millimetrovye volny i fotosinteziruyushchie organizmy* (Millimeter Waves and Photosynthetic Organisms), Moscow: Radiotekhnika, 2003.
52. Nikolaev, Yu.A., Distant Interactions Between Bacterial Cells, *Mikrobiologiya*, 1992, vol. 61, no. 6, pp. 1066–1071.
53. Matsuhashi, M.., Shindo, A., Ohshina, H., Tobi, M., Endo, S., Watanabe, H., Watanabe, H., and Pankrushina, A.N., Cellular Signals Regulating Antibiotic Sensitivities of Bacteria, *Microbial Drug Res*, 1996, vol. 2, no. 1, pp. 91–93.
54. Nikolaev, Yu.A., Mulyukin, A.L., Stepanenko, I.Yu., and El'-Registan, G.I., Autoretulyatsiya stressovogo otveta mikroorganizmov, *Mikrobiologiya*, 2006, vol. 75, no. 4.
55. Smirnov, S.G., Bacterial Ethology, a New Direction in Prokaryote Research, in *Fiziko-khimicheskie issledovaniya patogennykh enterobakterii v protsesse kul'tivirovaniya* (Physicochemical Research on Pathogenic Enterobacteria During Cultivation), Ivanovo: Ivanovskii gosudarstvennyi meditsinskii institut, 1985, pp. 5–10.
56. Oleskin, A.V., Superorganismal Level of Interaction in Microbial Populations, *Mikrobiologiya*, 1993, vol. 62, no. 3, pp. 389–403.
57. Oleskin, A.V., Social Behaviour of Microbial Populations, *J. Basic Microbiol.,* 1994, vol. 34, no. 6, pp. 425–439.
58. Shapiro, J.A., Bacteria as Multicellular Organisms, *Scientific American*, 1988, no. 8, pp. 46–54.
59. Corning, P., *Nature's Magic. Synergy in Evolution and the Fate of Humankind*, Cambridge: (Mass.): Cambridge Univ. Press, 2003.
60. Sherstobaev, K.N., On the Movement of Bacterial Colonies, *Mikrobiologiya*, 1961, vol. 30, pp. 91–98.
61. Puzyr', A.P. and Mogil'naya, O.A., Electron Microscopic Study of the Structure of Colonies of Some Bacterial Species, Krasnoyarsk: Institut fiziki SO AN SSSR, *Preprint no. 886*, 1988.
62. Puzyr', A.P., Mogil'naya, O.A., and Tirranen, L.S., Architectonics of Flavobacterium sp. 56 and Flavobacterium sp. 22 Colonies as Exposed by Transmission Electron Microscopy, *Mikrobiologiya*, 1998, vol. 67, no. 5, pp. 672–679 [*Microbiology* (Engl. Transl., 1998, vol. 67, no. 5, pp. 555-562].
63. Budrene, E.O., Formation of Spatially Ordered Structures in Colonies of Motile Bacteria on Agar, *Dokl. Akad. Nauk SSSR*, 1985, vol. 383, no. 2, pp. 470–473.
64. Budrene, E.O. and Berg, H., Dynamics of Formation of Symmetrical Patterns by Chemotactic Bacteria, *Nature*, 1995, vol. 376, pp. 49–53.
65. Botvinko, I.V., Bacterial Exopolysaccharides, *Usp. Mikrobiol.*, 1985, vol. 20, pp. 79–122.
66. Oleskin, A.V., Botvinko, I.V., and Tsavkelova, E.A., Colonial Organization and Intercellular Communication in Microorganisms, *Mikrobiologiya*, 2000, vol. 69, no. 3, pp. 309–327 [*Microbiology* (Engl. Transl.), vol. 69, no. 3, pp 249–265].
67. Kinsinger, R.F., Kearns, D.B., Hale, M., and Fall, R., Genetic Requirements for Potassium Ion-Dependent Colony Spreading in *Bacillus subtilis, J. Bacteriol.*, 2005, vol. 187, no. 24, pp. 8462–8469.
68. Keshavan, N.D., Chowdhury, P.K., Haines, D.C., and *González*, J.E., L-Canavanine Made by *Medicago sativa* Interferes with Quorum Sensing in *Sinorhizobium meliloti, J. Bacteriol.*, 2005, vol. 187, pp. 8427–8436.
69. Greenberg, E.P., Tiny Teamwork. Bacterial Communication, *Nature*, 2003, vol. 424, p. 134.
70. Gradova, N.B., Rodionova, G.S., and Mikhalev, V.V., The Main Microbiological Problems in Growing Fodder Yeast on Media with Oil Hydrocarbons, *Mikrobiologicheskii Sintez,* 1970, no. 1, pp. 21–28.