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A. Nurzhanova[1*], A. Muratova[2], R. Berzhanova[3], V. Pidlisnyuk[4], A. Nurmagambetova[1], A. Mamirova[1,3]

[1]Institute of Plant Biology and Biotechnology, Almaty, Kazakhstan;
[2]Institute of Biochemistry and Physiology of Plants and Microorganisms, Saratov, Russian;
[3]Al-Farabi Kazakh National University, Almaty, Kazakhstan;
[4]Jan Evangelista Purkyně University, Usti nad Labem, Czech.
E-mail: gen_asil@mail.ru

RHIZOSPHERE MICROORGANISMS: INCREASING PHYTOTECHNOLOGY PRODUCTIVITY AND EFFICIENCY – A REVIEW

Abstract. The review contains information on rhizobacteria with plant growth promoting properties (PGPR), on plant mechanisms of bacterial defense against heavy metal pollution and on stimulation of plant growth by nitrogen fixation, phosphorus dissolution, siderophores, phytohormones and ACC deaminase enzyme synthesis. PGPRs are classified according to their functionality, the degree of proximity to the root and the closeness of their association with the plant, and the site of bacterial colonization, and information is provided on the taxonomic affiliation of PGPRs. Issues of phytoremediation of soils contaminated with heavy metals and methods to improve process efficiency using rhizospheric microorganism inoculants are highlighted in the review, as phytoremediation is an economically viable and environmentally friendly technology. The review considers the role of association of endophytic and rhizospheric PGPBs with a plant in enhancing the efficiency of phytoaccumulation and phytostabilisation of soils contaminated with toxic metals and plant productivity.

Key words: Plant, rhizosphere, PGPB, mechanism, productivity, phytoremediation.

А.А. Нуржанова[1]*, А.Ю. Муратова[2], Р.Ж. Бержанова[3], V.V. Pidlisnyuk[4], А.С. Нурмагамбетова[1], А.А. Мамирова[1,3]

[1]Өсімдіктер биологиясы және биотехнологиясы институты, Алматы, Қазақстан;
[2]Өсімдіктер мен микроорганизмдердің биохимиясы және физиологиясы институты, Саратов, Ресей;
[3]әл-Фараби атындағы Қазақ Ұлттық Университеті, Алматы, Қазақстан;
[4]Jan Evangelista Purkyne University, Usti nad Labem, Czech Republic.
E-mail: gen_asil@mail.ru

РИЗОСФЕРАЛЫҚ МИКРООРГАНИЗМДЕР: ФИТОТЕХНОЛОГИЯНЫҢ ӨНІМДІЛІГІН АРТТЫРУ ЖӘНЕ ОНЫҢ ТИІМДІЛІГІ

Аннотация. Мақалада өсімдіктердің өсуін ынталандыратын қасиеттері бар (PGPR), ауыр металдармен ластанған ортадан өсімдіктерді бактериялық қорғау механизмдері және азотты бекіту, фосфорды еріту, сидерофорлар, фитогормондар және АЦК-деаминазы ферментін синтездеу арқылы өсімдіктердің өсуін ынталандырушы ризосфералық бактериялар туралы ақпарат ұсынылады. Функционалдылығы, тамырға жақындық дәрежесі және олардың өсімдікпен байланысының жақындығы, бактериялардың колонизациялану орны бойынша PGPR классификациясы қарастырылды, PGPR-дің таксономиялық тиістілігі туралы деректер келтірілді. Мақалада ауыр металдармен ластанған топырақты фиторемедиациялау мәселелеріне және оның ризосфералық микроорганизмдер-инокулянттардың көмегімен тиімділігін арттыру әдістеріне ерекше назар аударылды, өйткені бұл технология экономикалық тиімді және экологиялық таза технология болып саналады. Сонымен қатар улы металдармен ластанған топырақтарды фитотұрақтандыру және фитожинақтау тиімділігін және өсімдік өнімділігін арттырудағы эндофитті және ризосфералық PGPR-дың өсімдікпен байланысының маңызы қарастырылады.

Түйін сөздер: өсімдік, ризосфера, PGPR-бактериялар, механизм, өнімділік, фиторемедиация.

А.А. Нуржанова[1]*, А.Ю. Муратова[2], Р.Ж. Бержанова[3], V.V. Pidlisnyuk[4], А.С. Нурмагамбетова[1], А.А. Мамирова[1,3]

[1]Институт Биологии и Биотехнологий растений, Алматы, Казахстан;
[2]Институт Биохимии и Физиологии Растений и Микроорганизмов, Саратов, Россия;
[3]Казахский Национальный Университет им. аль-Фараби, Алматы, Казахстан;
[4]Jan Evangelista Purkyne University, Usti nad Labem, Czech.
E-mail: gen_asil@mail.ru

РИЗОСФЕРНЫЕ МИКРООРГАНИЗМЫ: ПОВЫШЕНИЕ ПРОДУКТИВНОСТИ И ЭФФЕКТИВНОСТИ ФИТОТЕХНОЛОГИИ

Аннотация. В обзоре представлены сведения о ризосферных бактериях, обладающих стимулирующими рост растений свойствами (PGPR), механизмах бактериальной защиты растений от загрязненной тяжелыми металлами среды и стимуляции роста растений посредством азотфиксации, растворения фосфора, синтеза сидерофоров, фитогормонов и фермента АЦК-деаминазы. Рассмотрены классификация PGPR по функциональности, степени близости к корню и тесноте ассоциации их с растением, места колонизации бактерии, приведены данные о таксономической принадлежности PGPR. Особый акцент в статье уделили вопросам фиторемедиации почвы, загрязненной тяжелыми металлами и методам повышения ее эффективности с помощью ризосферных микроорганизмов-инокулянтов, так как данная технология является экономически выгодной и экологически безопасной технологией. В обзоре рассматривается роль ассоциации эндофитных и ризосферных PGPR с растением в повышении эффективности фитоакумуляции и фитостабилизации почв, загрязненных токсичными металлами и продуктивности растений.

Ключевые слова: растение, ризосфера, PGPR-бактерии, механизм, продуктивность, фиторемедиация.

Introduction. The organs of higher plants represent a special ecological niche inhabited by microorganisms. In the course of their development, they act as centers for the formation of microbial communities - epiphytic, which settle on the surface of various plant organs, or endophytic, which invade, colonize and multiply in plant tissues (Bulgarelli et al., 2013; Feoktistova et al., 2016). Microorganisms living on the surface of above-ground plant organs are called phyllospheric, while those living in the root zone are called rhizospheric. The roots of plants are surrounded by soil - a medium densely populated by various microorganisms. The distance from the root determines how close the relationship is between the plants and the microorganisms living in their root zone. The soil microorganisms inhabiting the rhizosphere (a narrow soil zone about 0 to 8 mm in diameter that directly surrounds the plant roots) or the rhizoplane (the surface of the plant roots) form more or less strong associations with the plant's root system and form specific rhizosphere communities. Such relationships are characterized by the terms "associative bacteria", "associative relationship", "associative symbiosis" (Döbereiner, 1983).

Rhizospheric microorganisms colonize the area around and on the surface of the root unevenly, mainly in its upper part, and attach themselves to the pores of the cell walls. The existence of microorganisms and strong associations in these ecological niches, both within the root tissue and in the rhizoplane and rhizosphere, is primarily due to the active secretion of various low molecular weight substances such as amino and organic acids, sugars and various secondary metabolites by the root cells (Fan et al., 2018; Mitter et al., 2016). The microorganisms were found to be unevenly distributed within the same root: abundance increases in the area of the young apical roots, where the maximum release of soluble organic compounds takes place (Vives-Peris et al., 2020).

Materials and methods. The rhizospheric effect, which characterizes the increased number and activity of microorganisms in the root zone, increases after seed germination and reaches a maximum during flowering and fruiting depending on the composition of root exudates during plant development (Ray et al., 2020; Weyens et al., 2009). Thus, the root zone of young plants is dominated by gram-negative bacteria of the genera Pseudomonas, Flavobacterium, Azotobacter, etc., which are replaced by gram-positive bacteria of the genus Bacillus and actinobacteria of the genera Mycobacterium and Streptomyces as the plants age (Feoktistova et al., 2016).

The specificity of the microorganisms in the rhizosphere of a given plant species can be taken into account, i.e., a symbiotic relationship can only be established between certain species, which determines the specificity of the symbiosis (Kidd et al., 2017). For example, Fan et al. (2018) investigated the species diversity of plant root-associated bacteria in 6 cultivated and 20 wild plant species. Using 16S rRNA gene sequence analysis, the authors showed that 446 bacterial isolates were distributed among four phyla (Proteobacteria, Firmicutes, Actinobacteria, and Bacteroidetes), 32 families, and 90 genera. Proteobacteria formed the largest group of isolates (240): 40% ectophytic and 60% endophytic bacteria. In the rhizosphere, representatives of the genera Bacillus and Pseudomonas dominated; the most important endophytes were Microbacterium and Pseudomonas. Some genera, such as Stenotrophomonas, Yersinia, Labrys, and Luteibacter, were associated with specific plant species.

For soil bacteria that have a positive effect on plant growth, live in the rhizosphere and rhizoplane of plants and have the ability to colonize the root surface, survive, multiply and compete with other microbiota, Kloepper et al. (1980) coined the term PGPR, i.e., rhizobacteria that stimulate plant growth. PGPRs are found not only around but also within plant roots (endophytic bacteria colonizing apoplastic spaces inside the plant). No soil bacteria have been found to colonize these spaces (Rosier et al., 2018; Santoyo et al., 2021). Taxonomically, PGPRs are extremely diverse and are divided into extracellular and intracellular depending on the degree of proximity to the root and the closeness of association with plant. Extracellular PGPRs: representatives of the genera Agrobacterium, Arthrobacter, Azotobacter, Azospirillum, Bacillus, Burkholderia, Caulobacter, Chromobacterium, Erwinia, Flavobacterium, Micrococcous, Pseudomonas, Serratia, etc., while intracellular PGPRs are representatives of the genera Allorhizobium, Azorhizobium, Bradyrhizobium, Mesorhizobium belonging to Rhizobiaceae family. The majority of rhizobacteria belonging to the intracellular group are gram-negative rods; a smaller proportion are gram-positive rods, cocci or pleomorphic rods (Bhattacharyya et al., 2012).

Mechanisms of plant growth stimulation by PGPRs. The mechanisms of the positive effect of rhizobacteria on plant vital activity vary (Hayat et al., 2010). PGPRs influence plant growth and development either directly or indirectly (Glick, 2012). Different bacteria can influence plant growth and development under different conditions by using both of these mechanisms together or separately (Ojuederie et al., 2017). Indirect stimulation of plant growth occurs by reducing or preventing the harmful effects of phytotoxic microorganisms. This may involve a reduction in the Fe available to phytopathogens in the rhizosphere, the synthesis of enzymes that lyse the cell walls of fungi, and competition with harmful microorganisms for a place on plant roots. The mechanism of plant growth stimulation is the antagonistic relationship between PGPRs and phytopathogenic microorganisms

(Chowdhury et al., 2015). Direct stimulation of plant growth consists of: 1) supplying the plant with substances synthesized by the bacteria or facilitating the entry of nutrients from the environment into the plant (e.g. microbial nitrogen fixation); 2) synthesizing siderophores that can dissolve and accumulate Fe from the soil and supply it to plant cells; 3) production of various phytohormones, including auxins (e.g. indolyl-3-acetic acid (IAA), cytokinins, and gibberellins) which can influence different stages of plant growth; 4) a mechanism to dissolve minerals such as phosphorus, which then becomes readily available to the plant; 5) enzymes that can influence plant growth and development (e.g. 1-aminocyclopropane-1-carboxylic acid (ACC) (Le et al., 2019; Shaposhnikov et al., 2011) The screening of rhizospheric and endophytic microorganisms for the presence of the above properties serves as a basis for obtaining an effective PGPR inoculant to enhance plant growth for economic purposes, both to increase the yield of food crops and to promote the development of phytoremediation agents on contaminated soils (Schmidt et al., 2018; Mamirova et al., 2019).

Nitrogen fixation. Nitrogen is a nutrient for plant growth and productivity. Although the atmosphere consists of ~78% nitrogen, it is not available to plants. The ability to biologically fix molecular nitrogen (N_2) is only possessed by prokaryotes, which convert N_2 into ammonia with the help of the enzyme nitrogenase. The highest intensity of N_2 fixation can be developed by those microorganisms that interact with plants and use the products of their photosynthesis to maintain nitrogenase activity. The N_2 fixation is carried out by a complex enzyme, nitrogenase (Kim et al., 1994). Structurally, the N_2 fixation system differs among bacterial genera. Most biological N_2 fixation occurs through the activity of Mo-nitrogenase, which is present in all diazotrophs (Spaepen et al., 2011). Dinitrogenase reductase provides electrons with high reducing power, while enzyme dinitrogenase uses these electrons to reduce N_2 to ammonia (Kim et al., 1994).

Genetic control of N_2 fixation occurs at several levels: ammonium, nif-specific, amino acid, oxygen, nitrate, molybdenum, and temperature levels (Spaynk et al., 2002).

N_2-fixing bacteria are divided into symbiotic characterized by nodules formation as a result of host-symbiont interaction, where rhizobia act as intracellular symbionts, and non-symbiotic or associative ones, which provide only a small amount of fixed N_2 necessary for the bacteria-associated host plant (Bhattacharyya et al., 2012; Glick, 2012; Spaepen et al., 2011). Bacteria from the following genera have a high potential for N_2 fixation: Azospirillum, Azotobacter, Achromobacter, Agrobacterium, Bacillus, Beijerinckia, Clostridium, Enterobacter, Herbaspirillum, Klebsiella, and Pseudomonas (Morgun et al., 2009).

Phosphate solubilization. Plants can only take up inorganic phosphorus and its concentration in soil is very low as most of the organic phosphorus present in soil is insoluble and may constitute 4-90% of the total phosphate (Yadav et al., 2015). Despite its high content in soil, phosphorus bioavailability limits the plant growth, development, and productivity. The concentration of phosphorus available to plants in soil solution is about 1 mM and rarely reaches 10 mM (Lambers et al., 2006). The ability of some microorganisms to convert insoluble phosphorus (organic and inorganic phosphates) into an available form such as orthophosphate is an important feature of PGPB for increasing crop yield (Khan et al., 2007; Rodríguez et al., 2006). Microorganisms can use two systems to increase the concentration of exogenous phosphate: 1) by hydrolyzing organic phosphates under the action enzymes (non-specific acid phosphatases, phytases, phosphonates, and C-P lyases); 2) by dissolving mineral phosphates through the production of organic and inorganic acids (Rodríguez et al., 2006). Phosphate-solubilizing bacteria include members of the genera Azospirillum, Azotobacter, Bacillus, Beijerinckia, Bradyrhizobium, Burkholderia, Enterobacter, Erwinia, Flavobacterium, Microbacterium, Pseudomonas, Rhizobium, and Serratia (Bhattacharyya et al., 2012; Morgun et al., 2009). The strains of Pseudomonas, Bacillus, and Rhizobium are among the most potent phosphate solubilizes (Rodríguez et al., 1999).

Inoculation of seeds or soil with phosphate-solubilizing bacteria improves the solubilization of bound soil phosphorus and applied phosphates, resulting in higher crop yields. The combination of phosphate application and bacteria can be a cheap source of phosphate fertilizer for crop production (Yadav et al., 2015).

Siderophores synthesis. To ensure the availability of Fe, PGPRs synthesize siderophores. Almost all facultative anaerobic and aerobic microorganisms (especially bacteria and fungi) produce extracellular siderophores that bind the iron necessary for their growth. Phytopathogens also produce their own siderophores, but unlike PGPR siderophores, they bind iron ions much more slowly. Among the fungi that synthesize siderophores, representatives of the genera Penicillium and Aspergillus dominate, while among the bacteria, representatives of the genera Achromobacter, Agrobacterium, Enterobacter, Pseudomonas, Serratia, Bacillus, and Pseudomonas dominate (Haas, 2014; Lawongsa et al., 2008). The main function of siderophores is to convert Fe bound to proteins or water-insoluble compounds into the ionic form Fe^{3+}

accessible to microorganisms (Loper et al., 1999; Rajkumar et al., 2006). However, in addition to main function, siderophores also have the ability to chelate other heavy metals such as Al^{3+}, Zn^{2+}, Cu^{2+}, Pb^{2+}, and Cd^{2+}, which can influence the homeostasis and resistance of microorganisms to heavy metals (Złoch et al., 2016).

Plant siderophores have a much lower affinity for iron. Therefore, plants in soils contaminated with metals are unable to accumulate significant amounts of Fe in the absence of bacterial siderophores. In order to alleviate the plants stress caused by high metal concentrations in the soil, microorganisms synthesize siderophores (Saha et al., 2016). PGPR siderophores have different chemical structures and usually have a high affinity for Fe, with which they form stable complexes that can be taken up by plants (Loper et al., 1999). In order to obtain the required amount of Fe from the environment, they have developed mechanisms that increase the solubility and dissolution rate of the Fe^{3+} oxyhydroxides prevalent in aerobic soils. Chemically, these mechanisms are based on the weakening of the Fe-O bond through reduction, chelation, and protonation. Physiologically, two different mutually exclusive strategies are distinguished: (1) release of siderophores capable of dissolving external Fe^{3+} and subsequent absorption of the Fe^{3+}-siderophore complex; (2) reduction of Fe^{3+} to absorb the more soluble Fe^{2+} ion. In higher plants, the increase in their ability to convert extracellular Fe^{3+} to Fe^{2+} is part of physiological and morphological events operating to achieve adequate internal Fe levels. This series of traits determines the efficiency of Fe content in a species or cultivar, which in turn influences the yield of economically important plants and the natural distribution of species.

Phytohormones synthesis. The microbial production of individual phytohormones such as auxins and cytokinins has been well studied (Selvakumar et al., 2008; Spaepen et al., 2007).

Auxins. Bacterial auxins initiate and elongate roots, develop lateral roots and root hairs, which is important for the active uptake of nutrients by the plant, its growth and resistance to stress (Frankenberger et al., 2020; Spaepen et al., 2007). The most important natural representative of auxins is indolyl-3-acetic acid (IAA). IAA can act as a mutual signaling molecule in interactions between microbes and plants. Microorganisms use the phytohormone in interactions with plants as a strategy to colonize them for a mutualistic or parasitic relationship (Spaepen et al., 2007). Interest in the microbial synthesis of IAA is also growing due to another recently discovered property of auxin in Arabidopsis, the plant protection from phytopathogenic bacteria (Spaepen et al., 2011). IAA can be synthesized not only by plants but also by 80% rhizobacteria (Duca et al., 2020). This ability is possessed by bacteria belonging to different genera such as Aeromonas, Acetobacter, Alcaligenes, Agrobacterium Azospirillum, Bradyrhizobium, Enterobacter, Commamonas, Rhizobium, Pseudomonas, and Xanthomonas (Weyens et al., 2009). The biochemical pathways and genetic regulation of IAA synthesis are under active investigation. Currently, 5 tryptophan-dependent pathways are distinguished (with the formation of the following key metabolites: indole-3-acetonitrile, indole-3-acetaldehyde, indole-3-acetamide, indole-3-pyruvate, and tryptamine) and a single tryptophan-independent pathway is suspected (Spaepen et al., 2007). Rhizobacteria that synthesize IAA from tryptophan are very diverse, but the most important genera are Azotobacter, Azospirillum, Enterobacter, and Klebsiella.

Cytokinins and gibberellins. Much less information is available on the microbial synthesis of cytokinins and gibberellins. Cytokinins stimulate cell division and increase the growth of plant tissues, stimulate shoot growth and inhibit root development. The effective stimulation of plant growth by bacterial cytokinins has been demonstrated by many researchers (Arkhipova et al., 2007; Gutiérrez-Mañero et al., 2001). Gibberellins are involved in changing the plant morphology and tissue growth, especially shoots. Microorganisms in the rhizosphere can also produce or modulate phytohormones under in vitro conditions, so that they can alter the content of phytohormones influencing the plant hormone balance and response to stress (Morgun et al., 2009). The gibberellins formation is characteristic of rhizospheric bacteria, mainly of the genera Azotobacter, Azospirillum, Pseudomonas, Bacillus, Flavobacterium, Clostridium, and Agrobacterium (Tsavkelova et al., 2006). Cytokinins are synthesized by rhizobacteria belonging to the genera Azotobacter, Azospirillum, Pseudomonas, and Bacillus (Morgun et al., 2009).

ACC-deaminase synthesis and its role in the phytohormone ethylene reduction. The phytohormone ethylene is very important for the normal development of a plant, especially in its early stages. The hormone is produced endogenously by almost all plants and is also produced by various biotic and abiotic processes in the soil and plays an important role in triggering various physiological changes in plants. Among the numerous effects of ethylene on plants (seed germination, morphogenesis, flower induction, fruit ripening), the most commonly observed are inhibition of elongation and growth of lateral roots, development of root hairs, usually in response to abiotic and biotic stresses. Ethylene is not only a plant growth regulator, but is also considered a stress hormone (Arshad et al., 2007; Lawongsa et al., 2008). Under stress conditions such as high salt concentrations, drought, extreme temperatures, high light intensity, flooding, radiation, insect injury and feeding, polyaromatic hydrocarbons, heavy metals and pathogenicity, endogenous ethylene levels are greatly increased, which negatively affects overall plant growth and response to stress (Deikman, 1997).

Higher plants produce the hormone ethylene from L-methionine via intermediate compounds (S-adenosyl-L-methionine and 1-aminocyclopropane-1-carboxylic acid, ACC) (Yang et al., 1984). Glick et al. (1998) suggested that microorganisms containing ACC deaminase, which degrades the ethylene precursor to ammonium and α-ketobutyrate, may act as PGPRs by eliminating ACC, thereby lowering ethylene levels in developing and/or stressed plants. The yield of ethylene produced by the plant decreases as a consequence of the ACC decline in the plant and its excretion by bacteria (Glick, 2003). Belimov et al. (2005) showed that bacteria of different origin having ACC deaminase activity stimulated plant growth in soils containing phytotoxic Cd concentrations. In addition, Wang et al. (2000) showed that bacterial strains exerting biocontrol and carrying ACC deaminase genes were able to protect plants more effectively against viral phytopathogens. To date, bacterial strains with ACC deaminase activity have been identified in a variety of genera, including Acinetobacter, Achromobacter, Agrobacterium, Alcaligenes, Azospirillum, Bacillus, Burkholderia, Enterobacter, Pseudomonas, Ralstonia, Serratia, and Rhizobium (Kang et al., 2010; Zahir et al., 2009).

PGPR bacteria are thought to attach to the seeds or roots surface of developing plants in response to tryptophan or other molecules present in plant secretions, whereupon the bacteria synthesize and secrete IAA, some of which can be taken up by the plant (Patten et al., 2002). This IAA, together with the plant's endogenous IAA, can stimulate growth and induce the synthesis of ACC synthase, which converts S-adenosyl-L-methionine to ACC. Some of the ACC formed in this way is isolated from the plant seeds or roots along with other low molecular weight compounds normally present in root exudates (Patten et al., 2002). ACC, which is present in plant secretions, is taken up by bacteria and subsequently converted to ammonium and α-ketobutyrate by ACC deaminase. This reduces the amount of ACC outside the plant, so that the plant has to release larger amounts of ACC to maintain the balance between external and internal amounts. Firstly, the bacteria cause the plant to synthesize more ACC than would be necessary, and secondly, they stimulate the release of ACC from the plant.

The literature data shows that rhizobacteria stimulating plant growth not only have the potential to survive under stressful conditions, but also stimulate plant growth.

PGPR application to increase plant productivity. A strong incentive for the study of PGPR in the 70-80s was its obvious prospects for solving the problems of agrobiotechnologies related to achieving consistently high and qualified yields. Soil microbiological studies focused primarily on achieving practical goals: soil fertility, biological plant protection against diseases, sources of biologically active substances - plant growth stimulants (Simpson et al., 2011; Singh et al., 2011). The PGPR beneficial effects on plant growth and nutrition through a number of mechanisms including N_2 fixation, synthesis of siderophores, phytohormones and ACC deaminase have spurred the PGPR strains commercialization (Glick et al., 1998). PGPRs were classified according to functionality into the following categories: biofertilisers (increasing the nutrients availability for plants); phytostimulants (stimulating plant growth by phytohormones); rhizoremediators (degradation of organic pollutants); biopesticides (disease control mainly through the production of antibiotics and antifungal metabolites) (Somers et al., 2004). Numerous actinomycetes (Micromonospora sp., Streptomyces spp., Streptosporangium sp., Thermobifida sp., etc.) as major components of the microbial communities in the rhizosphere, which have inhibitory effects on various pathogens, are used as biocontrol agents to reduce plant infections and diseases and contribute to normal growth and development (Bhattacharyya et al., 2012; Glick, 2012). Currently, many bacteria (Agrobacterium, Alkaligenes, Arthrobacter, Azotobacter, Azospirillum, Bacillus, Burkholderia, Brevibacterium, Caulobacter, Chromobacterium, Enterobacter, Flavobacterium, Gluconacetobacte, Klebsiella, Micrococcus, and Pseudomonas) are commonly used as vaccines and actively included in commercial organic products and biofertilisers as an alternative to chemical ones polluting environment (Ortíz-Castro et al., 2009; Simpson et al., 2011; Singh et al., 2011). The process of Fe binding by PGPR siderophores leads to phytopathogens growth inhibition and plant growth enhancement, therefore, they are used as bacterial fertilizer (Bhattacharyya et al., 2012; Jing et al., 2007).

In recent decades, the scope of PGPR has expanded and they are now being considered not only for agriculture but also for soil bioremediation, as many PGPRs are resistant to pollutants (Belimov et al., 2009).

Based on the knowledge of plant-bacteria association interaction and examples of improvement of plant growth and nutrition by inoculation with beneficial microorganisms, the role of some biotic and abiotic factors in these interactions is studied and the possibility of using associative bacteria to increase plant resistance to various stresses is evaluated (Belimov et al., 2005, 2009). Microorganisms have different mechanisms of biological plant defense that manifest themselves both at the cellular level and at the population level. The interaction of plants and PGPRs aims at joint survival in a plant-microbial association under adverse environmental conditions. They can minimize the harmful effects of pollutants through reduction, oxidation, methylation or demethylation, compartmentalization and transformation to a less toxic state in the composition of engineered plant-microbial complexes (Hassan et al., 2017). Identifying the effect of enhanced biodegradation of pollutants in the root zone was the reason for combining the efforts of plant physiologists and microbiologists in developing phytoremediation biotechnology - the use of plants and their associated microorganisms to cleanse the environment matrices - and is considered the most promising approach due to its low cost and environmental friendliness. Isolation, screening and bacterization of plants with heavy metal-resistant PGPRs is considered an important tool to improve growth and increase the efficiency of phytoremediation of soils (Cho, 2020; Ojuederie et al., 2017).

Applying PGPRs to improve phytoremediation efficiency of heavy metals-contaminated soils. Phytoremediation strategies using rhizobacteria adapted to heavy metals are attracting more and more attention, as soil contamination with toxic elements is a serious environmental problem that negatively affects human health and agriculture. Phytoremediation is a promising method for the remediation of environments contaminated with heavy metals. However, there is a limitation: long remediation time, low biomass, inhibition of growth and development, and slow and limited bioavailability of some elements (Karimi et al., 2017; Kong et al., 2017).

Various agricultural practices, growth regulators and microbial organisms are used to improve biomass production and increase phytoremediation efficiency (Hu et al., 2018; Nebeská et al., 2019). Of particular interest is the study of rhizospheric bacteria, which belong to the PGPRs, as they are resistant to metals in the composition of engineered plant-microbial complexes while having a growth-promoting effect on phytosanitizing plants (Oh et al., 2015; Ullah et al., 2015). Endophytic or rhizobacterial microorganisms are used in the establishment of plant-microbial associations (Kidd et al., 2017; Ren et al., 2019). The main advantage of using endophytic microorganisms in conjunction with plants in phytoremediation is that any toxic xenobiotic ingested by the plant can be degraded within the plant, reducing phytotoxic effects and eliminating toxic effects on herbivorous animals living in or near contaminated areas (Ryan et al., 2008). Siciliano et al. (2001) studied the endo- and rhizosphere microbiomes of different grass species growing in oil-contaminated and nitroaromatic soils and found that contaminant concentration was the most important factor determining the structure and function of the rhizosphere and root endosphere microbiome. In addition, the plant-specific and selective effect influenced the prevalence of specific catabolic genes. Thus, the cane fescue rhizosphere community was characterized by the enrichment of catabolic genes such as alkane monooxygenases, naphthalene dioxygenases and nitrotoluene monooxygenases, while the predominance of catabolic genes in the clover rhizosphere decreased (Siciliano et al., 2003). This suggests that plants can control microbial signs of degradation in the rhizosphere and thus phytoremediation activity.

There is a great deal of information in the literature that under the effect of PGPR both the removal of heavy metals by plants and their entry into the plants increases. Given the differences in the attitude of plants and microorganisms towards elements, two mechanisms are therefore being considered in phytotechnology: phytoextraction and phytostabilisation (Ma et al., 2011). Bacteria from the PGPR group can improve the regenerative capacity of plants or reduce the phytotoxicity of polluted soils. In addition, plants and bacteria can form specific associations in which the plant provides the bacteria with a specific carbon source that induces the bacteria to reduce the phytotoxicity of the contaminated soil. On the other hand, plants and bacteria can form non-specific associations in which normal plant processes stimulate a microbial community that degrades contaminants in the soil through normal metabolic activities (Jing et al., 2007).

Phytoaccumulation or phytoextraction is the ability of a plant organism to extract pollutants from contaminated soils and accumulate them in aboveground organs. Phytoextraction involves the use of plants capable of accumulating metals in aboveground organs (Cunningham et al., 1996). Contaminated plant biomass must be disposed of and transported to special landfills to reduce the transfer of contaminants through the food chain. Disposal of contaminated biomass is believed to be more cost effective than disposal of contaminated soils (Arthur et al., 2005). PGPR-associated strains contribute to the uptake of metals by the plant from the soil through an increase in root surface area, the formation of root hairs, an increase in the solubility of elements, and their transfer in the soil-root-aboveground biomass system. These properties of microorganisms are used in phytoextraction technology (Glick, 2014; Visioli et al., 2015).

Heavy metals can be toxic to metal-accumulating and metal-tolerant plants if the metal concentration in the environment is high enough. This is partly attributed to iron deficiency in a number of different plant species in soils contaminated with heavy metals. Furthermore, low Fe content in plants grown in the presence of high heavy metal concentrations usually causes these plants to become chlorotic, as iron deficiency inhibits both chloroplast development and chlorophyll biosynthesis (Imsande, 1998). Therefore, microbial siderophores are used as iron chelators that can regulate iron availability in the rhizosphere of plants (Loper et al., 1999). In addition, low iron content in plants grown in the presence of high heavy metal concentrations usually causes these plants to become chlorotic, as iron deficiency inhibits both chloroplast development and chlorophyll biosynthesis (Imsande, 1998). However, microbial iron siderophore complexes can be taken up by plants and thus serve as a source of iron for plants. Therefore, it has been suggested that the best way to prevent plants from becoming chlorotic in the presence of high heavy metal concentrations is to provide them with a siderophore-producing bacterium. This suggests that some plant growth-promoting bacteria can significantly increase plant growth in the presence of heavy metals, including nickel, lead and zinc (Burd et al., 2000), allowing plants to develop longer roots and better rooting in the early stages of growth (Glick et al., 1998). The results of the study suggest that inoculation of plants PGPB with siderophore-producing bacteria can improve the bioavailability of elements, thereby accelerating the process of remediation of metal-contaminated soils by phytoextraction. Siderophore-producing PGPB strains help reduce plant stress by forming stable complexes with environmentally hazardous toxic metals such as Cd, Cu, Cr, Pb and Zn (Rajkumar et al., 2006). For example, in the article by Złoch et al. (2016), the selection of the most effective strains of siderophore-producing bacteria isolated from the roots (endophytes) and rhizosphere of Betula pendula L. and Alnus glutinosa L. growing at two sites contaminated with heavy metals in southern Poland, the siderophore-producing bacterial strains were found to be more numerous in the rhizosphere (47%) than in the root (18%). The strains from the genus Streptomyces synthesized of siderophores most efficiently. Under the stress of Cd^{2+} in the soil, Streptomyces sp. secreted three types of siderophores - hydroxamates, catecholates, and phenolates. Addition of an element to the soil increased the synthesis of siderophores, especially the synthesis of ferrioxamine. Siderophore-producing Pseudomonas aeruginosa increased the uptake of Cr and Pb by shoots when Zea mays was inoculated. The translocation coefficient was 4.3 and 3.4, respectively (Braud et al., 2009).

Phytohormones such as IAA released by PGPR also induce plant growth, are responsible for metal uptake and activate the plant defense response against heavy metal stress (Spaepen et al., 2011). It is believed that in addition to the production of siderophores, auxin, glutathione, low and high molecular weight proteins, intracellular polyphosphate granules and polyhydroxy butyric acid (Kulaeva et al., 2004). For example, when Populus euphraticaa was inoculated with a PGPB strain of Phyllobacterium sp. C65 that produced auxin, production decreased when the zinc concentration in the medium increased. The C65 strain helped Populus euphraticaa extract zinc more efficiently from the polluted environment, facilitating growth inhibition caused by heavy metals (Zhu et al., 2015). Bacteria are known to alter the ability of plants to bioaccumulate metals by releasing metal-immobilizing extracellular polymeric substances as well as metal-mobilizing organic acids and biosurfactants (Ma et al., 2016). PGPRs produce ACC deaminase, which reduces the production of the stress hormone ethylene. Extracellular polymeric substances secreted by bacteria, mainly consisting of polysaccharides, proteins, nucleic acids and lipids, play an important role in complexing with metals, reducing their bioavailability (Pinto et al., 2018).

The use of PGPRs does not always lead to increased uptake of metals by plants and soil remediation. PGPRs can reduce the mobility of metals through the mechanisms of biosorption and bioaccumulation (Pratush et al., 2018). In biosorption, metals are immobilized through various microbial processes such as precipitation, accumulation, sequestration and transformation (Ma et al., 2016). In addition, the ionic state of heavy metals (Cr, Fe, Mn, Hg, and Se) is influenced by reduction and/or oxidation, which transform the toxic mobile form into a less toxic immobile form (Ma et al., 2011).

Results and discussion. Phytostabilisation is based on the ability of plants or plant compounds to stabilize soil pollutant levels at low levels by depositing heavy metals or reducing the valence of metals in the rhizosphere, absorption and sequestration in root tissues, or adsorption on root cell walls (Gerhardt et al., 2017; Kumpiene et al., 2012). An advantage of phytostabilisation is that it does not require the removal of hazardous biomass compared to phytoextraction. In phytostabilisation, plants that are highly resistant to metals can be used to immobilize heavy metals in the subsurface and reduce their bioavailability. This prevents their migration into the ecosystem and reduces the likelihood of metals entering the food chain. The use of plant-associated bacteria capable of synthesizing IAA and other indole derivatives in the medium is thought to increase the flow of exudates into the rhizosphere. This leads to intensive proliferation of the bacteria and binding of elements in chelate complexes. As a result, plants can accumulate more pollutants due to the increased solubility and bioavailability of toxic heavy metals. The ability to synthesize auxins, found in many bacterial strains, e.g., from the genera Azospirillium, Pseudomonas and Bacillus, activates the growth of plant roots and provides a strategy for their colonization (Dodd et al., 2010). It is believed that the increased synthesis of bacterial IAA under the influence of Pb^{2+} and Cd^{2+} ions lead to increased exudation of carbon compounds and lectins by plant roots, which in turn leads to increased colonization of plant roots by microorganisms (Pishchik et al., 2016). Over time, the number of populations on the roots reaches a state of equilibrium as some of the populations migrate from the rhizoplane to the rhizosphere. As the number of bacteria in the rhizosphere increases, so does the number of free Pb^{2+} and Cd^{2+} ions bound in chelate complexes that are inaccessible to the plants. As a result, the uptake of metals by plants decreases significantly (up to 6-fold). The use of plant-associated bacteria capable of synthesizing IAA and other indole derivatives in the medium increases the flow of exudates into the rhizosphere. This leads to an intensive proliferation of the bacteria and the binding of elements in chelate complexes. As a result, the plants can accumulate more pollutants due to the increased solubility and bioavailability of toxic heavy metals. Yongpisanphop et al. (2021), an S3 strain was isolated from the rhizosphere of Pityrogramma calomelanos, which grows on heavily Pb-contaminated soils, produces siderophores and is unable to dissolve phosphate. Partial analysis of the 16S rRNA gene identified this isolate as a strain phylogenetically closely related to Arthrobacter humicola. When inoculated with the isolated Pityrogramma calomelanos strain, the authors showed Pb immobilization, leading to the conclusion that this strain can be recommended for lead phytostabilisation. Enhancement of phytoremediation of lead in soil using the wild species Onopordum acanthium by inoculation with some arbuscular mycorrhizal fungi and PGPR was found to increase Pb bioavailability, dry matter yield of shoots and roots, and absorption of the element by the plant (Karimi et al., 2017), mainly through the root system. When inoculated with arbuscular mycorrhizal fungi and PGPR, the Pb concentration in the O. acanthium root was 1.75-2.71 and 1.25-1.53 times higher than in the control (non-inoculated plants). Furthermore, the article by Shabaan et al. (2021) confirmed that PGPRs are an effective means of reducing Pb mobility and can be used effectively for phytostabilisation. The authors showed that the length of shoots and roots of Pisum sativum L. inoculated with PGPR when grown on soils contaminated with Pb at concentrations of 0, 250, 500 and 750 mg kg^{-1} increased by 21, 15, 18% and 72, 80, 84%, respectively, compared to non-inoculated control. Fresh biomass of shoots and roots also increased at Pb concentrations of 250, 500 and 750 mg kg^{-1} by 51, 45, 35% and 57, 101, 139%, respectively. Moreover, PGPR inoculation reduced Pb concentration in roots and shoots by 57, 55, 49%, and 70, 56, 58%, respectively, compared to the control (non-inoculated plants). The authors suggest using PGPR to improve the efficiency of phytostabilisation of soils contaminated with the toxic element lead. Lead is a very harmful and second most toxic element in nature, characterized by high persistence. It is ranked number one on the list of priority hazardous substances and causes adverse effects when released into a living system (Shabaan et al., 2021). Furthermore, Hassan et al. (2017) showed the effect of PGPR Bacillus cereus and Pseudomonas moraviensis on wheat yield on saline soil contaminated with trace elements. The authors found the maximum decrease in the coefficient of biological concentration for Cd, Co, Cr and Mn. Inoculation of wheat with the P. moraviensis strain reduced the biological accumulation factor, the translocation factor for Cd, Cr, Cu, Mn and Ni.

Thus, regulating the accumulation of heavy metals through PGPR is at the heart of a strategy to address the consequences of environmental pollution. Phytostabilization technology (conversion of chemical compounds into a less mobile and active form) is promising for obtaining environmentally friendly products, as the problem of disposing of the polluted biomass is eliminated, unlike phytoextraction technology. The site for phytoremediation is specific, i.e., the use of plants in certain soils and under certain climatic conditions does not guarantee their successful use in others. The specificity of the interaction of PGPR with heavy metal resistance depends on the soil environment, plant type, bioavailability of metal contaminants, composition of root exudates and nutrient content. The daily increasing contamination of soils and water bodies with plant metals can best be managed by interaction with metal-resistant PGPR. This has been the impetus for new research and the identification of potential PGPRs that play an effective role in phytoremediation (Shinwari et al., 2015).

Conclusion. Analysis of scientific literature data indicates that PGPRs in the composition of engineered plant-microbial complexes help the plant tolerate high metal toxicity due to their resistance to metals and their simultaneous ability to positively affect phytoremediation productivity. By altering the solubility and thus the bioavailability of metals, PGPRs have the potential to improve phytoremediation processes and contribute to an increase in the accumulation of heavy metals in plants, their migration in the “soil - root - soil part of the plants” system (this property is used in phytoextraction technology) or their localization mainly in the root system, i.e., transfer to a less mobile and active form through phytostabilisation.

Undoubtedly, the question of the relationship between bacteria and plants in plant-microbial associations requires fundamental investigation. How do plants form a microbial community in their root zone that is closely associated with plants in the presence of environmental pollutants, and how does inoculation of plants with microorganisms that stimulate their growth promote soil purification? One of the complex issues in the relationship between bacteria and plants in plant-microbial associations is the problem of the genetic mechanism of plants that determines the ability of a plant to interact with beneficial microorganisms. In this context, ohmic technologies such as metagenomics, metaproteomics, metatranscriptomics, etc. have been actively developed in recent years to better understand the function and interaction of plants and associated microorganisms. It is believed that the combination of phytotechnology and ohmic technologies can open up new opportunities for phytoremediation in persistent pollution. known or emerging pollutants (Vocciante et al., 2022).

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Information about authors:

Nurzhanova Asil – Doctor of Biological Sciences, Professor, Institute of Plant Biology and Biotechnology, Has an H-index: 7 (Scopus) (Scopus ID: 15029299700, https://www.scopus.com/authid/detail.uri?authorId=15029299700, https://orcid.org/0000-0003-4811-0164;

Muratova Anna – Doctor of Biological Sciences, Institute of Biochemistry and Physiology of Plants and Microorganisms, amuratova@yahoo.com, https://orcid.org/0000-0003-1927-918X;

Berzhanova Ramza – Candidate of Biological Sciences, Al-Farabi Kazakh National University, ramza05@mail.ru, https://orcid.org/0000-0001-9251-4452;

Pidlisnyuk Valentina – Doctor of Chemical Sciences, professor, Jan Evangelista Purkyně University, Usti nad Labem, Czech Republic, pidlisnyuk@gmail.com, https://orcid.org/0000-0002-1489-897X;

Nurmagambetova Asiya – Master, Institute of Plant Biology and Biotechnology, asiyanurm@mail.ru, https://orcid.org/0000-0001-6945-1983;

Mamirova Aigerim – PhD, Al-Farabi Kazakh National University, aigerim.mamirova@mail.com, https://orcid.org/0000-0002-4274-5081.

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К 110-летию ученого

У.М. АХМЕДСАФИН – ОСНОВАТЕЛЬ ГИДРОГЕОЛОГИЧЕСКОЙ НАУКИ В КАЗАХСТАНЕ

В.И. Данилов-Данильян
Институт водных проблем РАН, член-корреспондент РАН
E-mail: ellina.shamfarova@gmail.com

У.М. Ахмедсафин – крупнейший ученый-энциклопедист, гидрогеолог, географ, эколог, Герой Социалистического Труда, пионер гидрогеологии в Казахстане, один из самых ярких представителей блестящей когорты ученых, с его именем связан расцвет казахстанской науки. Он является автором уникальной методики поиска подземных вод в зоне засушливых пустынь.

Его труды, научные открытия намного пережили ученого, и актуальность их в условиях дефицита пресной воды на планете чрезвычайно возрастает. Работая в сложных климатических условиях, он обследовал огромные пространства знойных песчаных пустынь Казахстана и Средней Азии, считавшиеся совершенно безводными, исходя из научных предпосылок, открыл многочисленные подземные моря, озера, реки, расшифровал и объяснил их происхождение, определил ресурсы и наметил широкие перспективы их использования на благо человечества.

После успешной защиты кандидатской диссертации в Московском геологоразведочном институте им. С. Орджоникидзе в 1940 году, по согласованию с вице-президентом АН СССР, академиком О.Ю. Шмидтом, был направлен в казахстанский филиал Академии наук СССР в г. Алма-Ате, где им впервые был создан Сектор гидрогеологии и инженерной геологии.

В года Великой Отечественной войны (1941-1945 гг.) У.М. Ахмедсафин организовал и возглавил комплексную экспедицию в пустынные районы республики для выявления возможностей нахождения и содержания эвакуированных на восток заводов, предприятий и скота: предстояло выяснить, имеется ли в пустынях достаточное количество подземных вод. Оказалось, что в обследованных районах Южного Казахстана песчаные пустыни не безводны и в них широко распространены доброкачественные подземные воды, пригодные для использования.

В 1947 г. У.М. Ахмедсафин защитил докторскую диссертацию в Москве. В 1951 году выпустил большую монографию «Подземные воды песчаных массивов южной части Казахстана». В этой работе и в ряде статей впервые в отечественной и зарубежной гидрогеологии всесторонне освещается инфильтрационное происхождение, накопление, распространение региональных ресурсов подземных вод, методов их определения. Выявленные при этом ресурсы доброкачественных подземных вод дали мощный импульс к развитию аридной гидрогеологии.

В годы освоения ценных земель У. Ахмедсафин возглавил гидрогеологические исследования в Северном Казахстане. Здесь были определены перспективные водоносные горизонты, содержащие значительные запасы подземных вод, за счет которых решена проблема водообеспечения 400 целинных совхозов, колхозов, многих районных центров, железнодорожных станций и т.д.

Более четверти века У. Ахмедсафин изучал глубинную гидрогеологию аридных районов. При этом им были установлены научные положения, имеющие первостепенное значение не только для Казахстана, но и для многих засушливых развивающихся стран. Они позволили ему впервые в истории гидрогеологических исследований у нас и за рубежом создать и опубликовать фундаментальные прогнозные карты артезианских бассейнов (с монографиями), выявить 70 артезианских бассейнов, оценить содержащиеся в них огромные вековые запасы доброкачественных подземных вод, равные 7,5 триллионам кубометров (соизмеримые с объемом 70-и озер Балхаш), ежегодно возобновляющиеся в размере 48 млрд.куб. метров.

В 1951 году У. Ахмедсафин избирается членом-корреспондентом, а в 1954 – академиком Академии наук Казахской ССР. В 1965 г. впервые организовал единственный в системе Академий наук СССР Институт гидрогеологии и гидрофизики.

Его крупные научные достижения позволили обеспечить подземной водой около 69 городов Казахстана, 4 тысячи населенных пунктов, обводнить 115 млн.га пастбищ, оросить до 60 тысяч га земель.

Обладая даром научного предвидения и большим практическим опытом, У. Ахмедсафин выступал против создания некоторых гидротехнических сооружений, могущих вызвать экологические катастрофы. Во многом его прогнозы подтвердились. Он единственный не подписал заключение правительственной комиссии о строительстве Кызылкумского канала, т.к. это привело бы к уменьшению притока реки Сырдарьи в Аральское море и тем самым способствовало бы усыханию Аральского моря.

Важным вопросом проблемы охраны окружающей среды была охрана озера Балхаш в связи со строительством Капчагайского водохранилища на реке Или. Строительство и забор значительного количества воды из реки Или на его заполнение могли привести озеро Балхаш к участи Аральского моря, т.е. к усыханию его крупной дельты. Ему потребовались большие усилия, научные доказательства, в том числе и на правительственном уровне, чтобы показать нецелесообразность строительства водохранилища и, уж во всяком случае не до проектной отметки. В результате удалось отстоять минимальную отметку заполнения водохранилища и нерасширения рисовых плантаций в низовьях реки Или. Таким образом удалось спасти озеро Балхаш хотя бы на период заполнения водохранилища.

Он также обосновал положение, что строительство гидротехнических сооружений на реках, протекающих в пустынных районах, может повлечь за собой усыхание водных бассейнов (озер), в которые они впадают. В зонах с повышенной сейсмической активностью – усиливать балльность землетрясений. В то же время правильное использование подземных вод в этих районах снижает балльность землетрясений.

У.М. Ахмедсафин являлся рьяным противником переброски Сибирских рек в Казахстан и Среднюю Азию. Совместными усилиями с учеными других Республик СССР принятие этого решения было приостановлено.

У.М. Ахмедсафин является основателем гидрогеологической науки и создателем школы аридной геологии в Казахстане. Им было подготовлено более 60 кандидатов и докторов наук. Кроме научной работы, занимался преподавательской деятельностью, заведовал кафедрой гидрогеологии и инженерной геологии в Казахском горно-металлургическом институте. В 1949 году ему было присвоено звание профессора.

У.М. Ахмедсафин был государственным деятелем. В 1955-59 годах избирался депутатом и членом Президиума Верховного Совета Казахской ССР IV созыва.

В 1955-60 гг. У.М. Ахмедсафин был членом Гидрогеологической секции Национального комитета геологов ЮНЕСКО. Он неоднократно оказывал помощь через ЮНЕСКО в гидрогеологических исследованиях во многих странах мира, в августе 1960 г. он сделал доклад на гидрогеологической секции Международного геологического конгресса в Копенгагене. В 1979 г. проводил международные курсы по линии ЮНЕП в Москве, Алма-Ате и Чимкенте по экологии пастбищ мира, на которых присутствовали представители африканских, арабских стран и Аргентины, неоднократно консультировал по вопросам орошения засушливых земель представителей Австралии, Израиля, Венгрии, Франции и Кувейта.

У.М. Ахмедсафин награжден многими правительственными наградами СССР. В 1969 году он был награжден высшей наградой СССР, ему было присвоено звание Героя Социалистического Труда.

У.М. Ахмедсафин опубликовал около 500 печатных работ: из них 18 монографий и 18 гидрогеологических карт.

Учитывая заслуги ученого, после его смерти его имя было присвоено созданному им Институту гидрогеологии и гидрофизики, одной из улиц Алма-Аты, учебному заведению на его родине в Северо-Казахстанской области.

100-летие ученого проводилось под эгидой ЮНЕСКО.

Светлой памяти

САДЫКОВОЙ АЛЛЫ БАЙСЫМАКОВНЫ

1 июля 2022 года на 76-м году жизни после непродолжительной болезни скончалась **Садыкова Алла Байсымаковна** – доктор физико-математических наук, академик Международной Евразийской академии наук (IEAS), заведующая лабораторией региональной сейсмичности ТОО Института сейсмологии МЧС Республики Казахстан.

Алла Байсымаковна – известный ученый, научный руководитель Программы «Оценка сейсмической опасности территорий областей и городов Казахстана на современной научно-методической основе», один из авторов карт сейсмического районирования территории Казахстана разной детальности и сейсмического микрорайонирования территории г. Алматы, входящих в перечень нормативных документов, регламентирующих проектирование и строительство в сейсмоактивных регионах Казахстана.

Алла Байсымаковна родилась в семье служащего в городе Шымкенте Южно-Казахстанской области 14 мая 1946 года, сразу после окончания Ленинградского вуза начала работать в секторе сейсмологии при Институте геологии Академии наук КазССР, на базе которого в 1976 г. был сформирован Институт сейсмологии. Здесь она защитила кандидатскую диссертацию в 1992 г., а затем в 2010 г. – докторскую на тему «Сейсмологические и геолого-геофизические основы вероятностной оценки сейсмической опасности Казахстана».

Алла Байсымаковна – автор более 160 научных и научно-методических работ, в т.ч. 7 монографий (в соавторстве) в области изучения особенностей проявления землетрясений, разработки методики долго- и среднесрочного прогноза землетрясений и оценки сейсмической опасности. Ее монография

«Сейсмическая опасность территории Казахстана» (Алматы, 2012, 267 с.) является фундаментальным трудом, где изложены результаты многолетних исследований особенностей сейсмичности и сейсмического режима территории Казахстана. Книга «Землетрясения Казахстана: причины, последствия и сейсмическая безопасность» (в соавторстве, Астана, 2019, 290 с.) является научно-популярным изданием о современном состоянии проблемы изучения землетрясений в Казахстане, где отмечены все трудности прогноза землетрясений и отведено место научным и общественным мерам противостояния стихии – сейсмозащите.

На протяжении многих лет Алла Байсымаковна была ученым секретарем межведомственной комиссии по прогнозу землетрясений и представляла нашу страну в международных организациях. Она активно сотрудничала со всеми сейсмологическими учреждениями, была членом различных республиканских комиссий, читала курс лекций по специальности «сейсмология» на кафедре геофизики КазНТУ им. Сатпаева. Ее неоднократные выступления по радио и телевидению, многочисленные интервью в средствах массовой информации были направлены на изложение знаний о землетрясениях – причинах их возникновения, связанных с ними опасностями, методах их изучения и возможностями прогноза.

Любовь к сейсмологии Алла Байсымаковна сохранила до конца жизни. До последнего дня она оставалась на работе, вкладывая в нее все физические и душевные силы, являя собой пример преданного и самоотверженного служения науке, высочайшей работоспособности и ответственности, целеустремленности, чуткости и бескорыстия, неравнодушного отношения к любой жизненной ситуации. Заслуги Садыковой А.Б. отмечены медалью за вклад в науку в честь 30-летия Независимости РК, грамотами, дипломами.

Благодаря высоким профессиональным и личным качествам Алла Байсымаковна пользовалась безусловным авторитетом среди казахстанских и зарубежных специалистов. Она прожила достойную жизнь уважаемого человека, глубокого мыслителя и преданного своему делу ученого. Более 45 лет она была вместе с мужем Е.Т. Садыковым, имея сына и четверых внуков.

1 июля 2022 перестало биться сердце этой удивительной женщины, но в наших сердцах всегда будет жить светлая память о ней. Мы будем помнить Аллу Байсымаковну как глубоко интеллигентного, отзывчивого, жизнерадостного, необычайно деятельного человека и талантливого ученого. Ее уход – большая потеря для науки Казахстана. Аллы Байсымаковны Садыковой больше нет с нами. Но осталось ее богатейшее научное наследие, ученики, которые будут продолжать дело своего наставника. Осталась добрая память об этом светлом, душевно щедром человеке.

От имени соратников и коллег по работе
профессор А. Нурмагамбетов

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