

# Supplementary Materials

## Bioactive Peptides Produced by Cyanobacteria of the Genus *Nostoc*: a Review

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**Table 1.** Peptides produced by cyanobacteria of the genus *Nostoc* (MW molecular weight).

Peptide name	MW	Strain, habitat & place of isolation	References
Aeruginosin 865	864	<i>Nostoc</i> sp. Lukešova 30/93 Terrestrial: Forest soil, Krušné mountains, Czech Republic	38
Anabaenopeptin	807 808 827 841 843 857	<i>Nostoc</i> sp. CENA543 Saline/alkaline: Salina 67 Mil Lake, Brazil <i>Nostoc</i> sp. ASN_M Freshwater: Paddy fields, Golestan province, Iran <i>N. punctiforme</i> PCC73102 Terrestrial: Isolated from <i>Macrozamia</i> sp., Australia	117 30 115
Banyascyclamide A	537	<i>Nostoc</i> sp. TAU IL-235	37
Banyascyclamide B	521	Freshwater: Banyas stream, Jordan River, Israel	
Banyascyclamide C	555		
Banyaside A	992	<i>Nostoc</i> sp. TAU IL-235	123
Banyaside B	949	Freshwater: Banyas stream, Jordan River, Israel	
Banyasin A	713	<i>Nostoc</i> sp. TAU IL-235 Freshwater: Banyas stream, Jordan River, Israel	123
Cryptophycin-1 (A)	654	<i>Nostoc</i> sp. ATCC 53789	47
Cryptophycin-2(B)	620	Terrestrial: Lichen, Arron Island, Scotland	
Cryptophycin-3 (C)	638	<i>Nostoc</i> sp. GSV 224	36, 51
Cryptophycin-4 (D)	604	Terrestrial: India	
Cryptophycin-16	640		
Cryptophycin-17	624		
Cryptophycin-18	638		
Cryptophycin-19	624		
Cryptophycin-21	640		
Cryptophycin-23	674		
Cryptophycin-24	606		
Cryptophycin-26	638		
Cryptophycin-28	624		
Cryptophycin-29	624		
Cryptophycin-30	656		
Cryptophycin-31	688		
Cryptophycin-38	654		

Cryptophycin-40	640		
Cryptophycin-43	590		
Cryptophycin-45	658		
Cryptophycin-46	638		
Cryptophycin-49	624		
Cryptophycin-50	640		
Cryptophycin-54	654		
Cryptophycin-175	672		
Cryptophycin-176	626		
Cryptophycin-326	675		
Cryptophycin-327	655		
Cyanopeptolin 962	962	<i>N. edaphicum</i> CCNP 1411	27
Cyanopeptolin 969	969	Brackish water: Gulf of Gdańsk,	
Cyanopeptolin 978	978	Baltic Sea	
Cyanopeptolin 985	985		
Cyanopeptolin 990	990		
Cyanopeptolin 992	992		
Cyanopeptolin 999	999		
Cyanopeptolin 1006	1006		
Cyanopeptolin 1013	1013		
Cyanopeptolin 1018	1018		
Cyanopeptolin 1020	1020		
Cyanopeptolin 1027	1027		
Cyanopeptolin 1048	1048		
Cyanovirin-N	11013	<i>N. ellipsoforum</i>	24
Hassallidin 1	1295	<i>Nostoc</i> sp. CENA 219	124
Hassallidin 2	1293	Freshwater: Brazil	
Hassallidin 3	1279	<i>N. calcicula</i> 6 sf calc	125
Hassallidin 4	1279	Dobré Pole, Czech Republic	
Hassallidin 5	1277		
Hassallidin 7	1313		
Hassallidin 8	1269		
Hassallidin 10	1281		
Hassallidin 11	1297		
Hassallidin 12	1297		
Hassallidin 14	1297		
Hassallidin 15	1297		
Hassallidin 17	1263		
Hassallidin 19	1297		
Hassallidin 20	1263		
Hassallidin 22	1263		
Hassallidin 24	1265		
Hassallidin 26	1297		
Hassallidin 27	1263		
Insulapeptolide A	941	<i>N. insulare</i> SAG 54.79	113
Insulapeptolide B	955	Terrestrial: Soil	
Insulapeptolide C	955		
Insulapeptolide D	969		
Insulapeptolide E	1020		
Insulapeptolide F	1006		
Insulapeptolide G	991		
Insulapeptolide H	1005		

[MeAsp <sup>3</sup> , Adda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin LA	908	<i>Nostoc</i> sp. BHU 001 Freshwater: Agricultural pond, India	126
[MeAsp <sup>3</sup> , Adda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin AR	952	<i>Nostoc</i> sp. BHU 001 Freshwater: Agricultural pond, India	126
[Leu/Ile <sup>2</sup> , Asp <sup>3</sup> , ADDA <sup>5</sup> , Mdha <sup>7</sup> ] microcystin	980	<i>Nostoc</i> sp. Treb K1/5 Pool no. 1 in the Collection of water a wetland plants, benthos Třeboň, Czech Republic	127
[MeAsp <sup>3</sup> , DMAdda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin LR	980	<i>Nostoc</i> sp. IO-102-I Terrestrial: Isolated from lichen, Sysmä, Finland	106
		<i>Nostoc</i> sp. NR1 Freshwater: Nile River, Egypt	128
[MeAsp <sup>3</sup> , Adda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin LR	995	<i>Nostoc</i> sp. BHU 001 Freshwater: Agricultural pond, India	126
[Asp <sup>3</sup> , ADMAdda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin LR	1008	<i>Nostoc</i> sp. 152 Freshwater: Lake Säaskjärvi, Finland	88, 103
		<i>Nostoc</i> sp. IO-102-I Terrestrial: Isolated from lichen, Sysmä, Finland	106
[Asp <sup>3</sup> , ADMAdda <sup>5</sup> , Dhb <sup>7</sup> ] microcystin LR	1008	<i>Nostoc</i> sp. DUN 901 Brackish water: Lake, UK	104
		<i>Nostoc</i> sp. NR1 Freshwater: Nile River, Egypt	128
[MeAsp <sup>3</sup> , DMAdda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin LR	1008	<i>Nostoc</i> sp. BHU 001 Freshwater: Agricultural pond, India	126
[MeAsp <sup>3</sup> , ADMAdda <sup>5</sup> , Mdhb <sup>7</sup> ] microcystin LR	1008	<i>Nostoc</i> sp. 152 Freshwater: Lake Säaskjärvi, Finland	103
[Asp <sup>3</sup> , Adda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin FR	1014	<i>Nostoc</i> sp. Treb K1/5 Pool no. 1 in the Collection of water a wetland plants, benthos Třeboň, Czech Republic	127
[Asp <sup>3</sup> , ADMAdda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin L-Har	1022	<i>Nostoc</i> sp. 152 Freshwater: Lake Säaskjärvi, Finland	103
[MeAsp <sup>3</sup> , ADMAdda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin LR	1022	<i>Nostoc</i> sp. 152 Freshwater: Lake Säaskjärvi, Finland	88, 103
		<i>Nostoc</i> sp. IO-102-I Terrestrial: Isolated from lichen, Sysmä, Finland	106
[Asp <sup>3</sup> , Adda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin YR	1030	<i>Nostoc</i> sp. Treb K1/5 Pool no. 1 in the Collection of water a wetland plants, benthos Třeboň, Czech Republic	127
[MeAsp <sup>3</sup> , Adda <sup>5</sup> , Dha <sup>7</sup> ] microcystin YR	1030	<i>Nostoc</i> sp. CENA88 Freshwater: Sao Paulo, Brazil	129
[MeAsp <sup>3</sup> , ADMAdda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin L-Har	1036	<i>Nostoc</i> sp. 152 Freshwater: Lake Säaskjärvi, Finland	130
[MeAsp <sup>3</sup> , ADMAdda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin XR	1036	<i>Nostoc</i> sp. IO-102-I Terrestrial: Isolated from lichen, Sysmä, Finland	106
[Asp <sup>3</sup> , ADMAdda <sup>5</sup> , Dhb <sup>7</sup> ] microcystin RR	1051	<i>Nostoc</i> sp. DUN 901 Brackish water: Lake, UK	104
[MeAsp <sup>3</sup> , Adda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin WR	1067	<i>Nostoc</i> sp. BHU 001 Freshwater: Agricultural pond, India	126

[Asp <sup>3</sup> , ADMAdda <sup>5</sup> , Dhb <sup>7</sup> ] microcystin HtyR	1072	<i>Nostoc</i> sp. DUN 901 Brackish water: Lake, UK	104
[MeAsp <sup>3</sup> , ADMAdda <sup>5</sup> , Mdha <sup>7</sup> ] microcystin XR	1076	<i>Nostoc</i> sp. IO-102-I Terrestrial: Isolated from lichen, Sysmä, Finland	106
Microviridin G	1805	<i>N. minutum</i> NIES-26	100
Microviridin H	1837	Terrestrial: Ishigaki, Japan <i>N. punctiforme</i> PCC73102 Terrestrial: Isolated from <i>Macrozamia</i> sp., Australia	95
Muscoride A	512	<i>N. muscorum</i> IAM M-14 Freshwater	131
Namalide B	575	<i>Nostoc</i> sp. CENA 543	117
Namalide D	559	Saline/alkaline: Salina 67 Mil Lake, Brazil	
Namalide E	545		
Namalide F	545		
Nodularin	824	<i>Nostoc</i> sp. 65.1 Terrestrial: Cycad symbiont, Australia	109, 132
Nodularin L-Har	838	<i>Nostoc</i> sp. 73.1 Terrestrial: Cycad symbiont, Australia	
Nostamide A	841	<i>N. punctiforme</i> PCC73102 Terrestrial: Isolated from <i>Macrozamia</i> sp., Australia	115 117
Nostamide B	805	<i>Nostoc</i> sp. CENA543	
Nostamide C	777	Saline/alkaline: Salina 67 Mil Lake, Brazil	
Nostamide D	777		
Nostamide E	777		
Nostocyclamide A	490	<i>Nostoc</i> sp. 31	133, 134
Nostocyclamide M	506	Freshwater	
Nostocyclin A (1)	1116	<i>Nostoc</i> sp. DUN 901 Brackish water: Lake, UK	114
Nostocyclopeptide A1	756	<i>Nostoc</i> sp. ATCC 53789	62
Nostocyclopeptide A2	790	Terrestrial: Isolated from lichen, Arron Island, Scotland	
Nostocyclopeptide A3	804	<i>Nostoc</i> sp. ASN_M Freshwater: Paddy fields, Golestan province, Iran	30
Nostocyclopeptide M1	881	<i>Nostoc</i> sp. XSPORK 13A Seawater: Isolated from gastropod, Cape of Porkkala, Baltic Sea	63
Nostofungicidine	1080	<i>N. commune</i> OK-1 Terrestrial: Okayama, Japan	40
Nostoginin BN 741	741	<i>Nostoc</i> sp. TAU IL-235	37
Nostoginin BN 578	578	Freshwater: Banyas, Jordan River, Israel	
Nostopeptolide A1	1080	<i>Nostoc</i> sp. GSV224	93
Nostopeptolide A2	1066	Terrestrial: India	
Nostopeptolide A3	1080	<i>Nostoc</i> sp. XPORK 5A	94
Nostopeptolide L1	1063	Seawater: Isolated from gastropod, Cape of Porkkala, Baltic Sea	
Nostopeptolide L2	1047	<i>Nostoc</i> sp. UK2aImI	94
Nostopeptolide L3	1049		
Nostopeptolide L4	1033	Terrestrial: Isolated from lichen	
Nostopeptin A	954	<i>N. minutum</i> Nies-26	112
Nostopeptin B	926	Terrestrial/Freshwater: Ishigaki, Japonia	

Nostopeptin BN 920	920	<i>Nostoc</i> sp. TAU IL-235 Freshwater: Banyas, Jordan River, Israel	37
Nostophyscin	888	<i>Nostoc</i> sp. 152 Freshwater: Sääksjärvi Lake, Finland	87, 92
Nostosin A	449	<i>Nostoc</i> sp. FSN	97
Nostosin B	451	Terrestrial/freshwater: Paddy fields, Golestan, Iran	
Nostoweipeptin W1	1214	<i>Nostoc</i> sp. XPORK 5A	94
Nostoweipeptin W2	1198	Brackish water: Gulf of Finland, Baltic Sea	
Nostoweipeptin W3	1198		
Nostoweipeptin W4	1200		
Nostoweipeptin W5	1200		
Nostoweipeptin W6	1200		
Nostoweipeptin W7	1172		
Schizopeptin 791	791	<i>Nostoc</i> sp. CENA543 Saline/alkaline: Salina 67 Mil Lake, Brazil	117
Tenuocyclamide A	459	<i>N. spongiaeforme</i> var. <i>tenue</i> TAU IL-184-6	135
Tenuocyclamide B	459	Terrestrial: Soil/Litophytic sample, Bet Dagan, Israel	
Tenuocyclamide C	505		
Tenuocyclamide D	521		

## References

123. Ploutno, A.; Carmeli, S. Banyasin A and banyasides A and B, three novel modified peptides from a water bloom of the cyanobacterium *Nostoc* sp. *Tetrahedron* **2005**, *61*, 575–583.
124. Vestola, J.; Shishido, T.; Jokela, J.; Fewer, D.; Aitio, O.; Permi, P.; Wahlsten, M.; Wang, H.; Rouhiainen, L.; Sivonen, K. Hassallidins, antifungal glycolipopeptides, are widespread among cyanobacteria and are the end-product of a nonribosomal pathway. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 1909–1917.
125. Shishido, T.; Humisto, A.; Jokela, J.; Liu, L.; Wahlsten, M.; Tamrakar, A.; Fewer, D.; Permi, P.; Andreote, A.; Fiore, M.; et al. Antifungal compounds from cyanobacteria. *Mar. Drugs* **2015**, *13*, 2124–2140.
126. Bajpai, R.; Sharma, N.; Lawton, L.; Edwards, C.; Rai, A. Microcystin producing cyanobacterium *Nostoc* sp. BHU001 from a pond in India. *Toxicon* **2009**, *53*, 587–590.
127. Kust, A.; Urajová, P.; Hrouzek, P.; Vu, D.; Čapková, K.; Štenclová, L.; Řeháková, K.; Kozlíková-Zapomělová, E.; Lepšová-Skácelová, O.; Lukešová, A.; et al. A new microcystin producing *Nostoc* strain discovered in broad toxicological screening of non-planktic Nostocaceae (cyanobacteria). *Toxicon* **2018**, *150*, 66–73.
128. Abu-Serie, M.; Nasser, N.; El-Wahab, A.; Shehawy, R.; Pienaar, H.; Baddour, N.; Amer, R. In vivo assessment of the hepatotoxicity of a new *Nostoc* isolate from the Nile River: *Nostoc* sp. strain NR1. *Toxicon* **2018**, *143*, 81–89.
129. Genuário, D.; Silva-Stenico, M.; Welker, M.; Moraes, L.; Fiore, M. Characterization of microcystin and detection of microcystin synthetase genes from a Brazilian isolate of *Nostoc*. *Toxicon* **2010**, *55*, 846–854.
130. Sivonen, K.; Namikoshi, M.; Evans, W.; Färdig, M.; Carmichael, W.; Rinehart, K. Three new microcystins, cyclic heptapeptide hepatotoxins, from *Nostoc* sp. strain 152. *Chem. Res. Toxicol.* **1992**, *5*, 464–469.
131. Nagatsu, A.; Kajitani, H.; Sakakibara, J. Muscoride A: A new oxazole peptide alkaloid from freshwater cyanobacterium *Nostoc muscorum*. *Tetrahedron Lett.* **1995**, *36*, 4097–4100.
132. Gehringer, M.; Pengelly, J.; Cuddy, W.; Fieker, C.; Forster, P.; Neilan, B. Host selection of symbiotic cyanobacteria in 31 species of the Australian cycad genus: *Macrozamia* (Zamiaceae). *Mol. Plant. Microbe Interact.* **2010**, *23*, 811–822.

133. Todorova, A.; Jüttner, F. Nostocyclamide: A new macrocyclic, thiazole-containing allelochemical from *Nostoc* sp. 31 (cyanobacteria). *J. Org. Chem.* **1995**, *60*, 7891–7895.
134. Jüttner, F.; Todorova, A.; Walch, N.; von Philipsborn, W. Nostocyclamide M: A cyanobacterial cyclic peptide with allelopathic activity from *Nostoc* sp. 31. *Phytochem.* **2001**, *57*, 613–619.
135. Banker, R.; Carmeli, S. Tenuocyclamide A-D, cyclic hexapeptides from the cyanobacterium *Nostoc spongiaeforme* var. *tenuis*. *J. Nat. Prod.* **1998**, *61*, 1248–1251.