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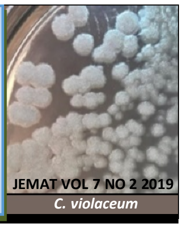

Applications, Pollution, Toxicity and Bioremediation of Acrylamide

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ABSTRACT

Acrylamide has many chemical and environmental uses. The main or principle use of acrylamide is in the production of high molecular weight polyacrylamides with up to 99.9% of acrylamide is estimated used to produce polyacrylamide. Acrylamide, in the form of polyacrylamides are used as binders and retention supports for fibres and to retain pigments on paper fibres, to decrease soil erosion, in furrow irrigation systems and in the formulation for the herbicide glyphosate. Acrylamide is a neurotoxic agent and its pollution remains an important global awareness due to its acute toxicity. Due to its toxicity, the maximum permissible limit for acrylamide containing in drinking water of Malaysia is 0.0005 mg/L. Its uses, toxicity, pollution and bioremediation are the subject of this mini review.

INTRODUCTION

Acrylamide is the foundation for the polymer, polyacrylamide (PAM). The production of commercial polyacrylamide may very well be contaminated with acrylamide, its toxic monomer. Consequently, suggestions have already been focused on the quantity of acrylamide that is contained in polyacrylamide. As an example, a restriction of 500 ppm in polyacrylamide formulations is utilized in agriculture or water treatment method. Some other uses of acrylamide include as sewage-flocculating agent [1], as adhesives, and in tunnels and dams stabilization [2]. Incidentally, one of the identified cases of acrylamide toxicity is due to its application for stabilizing of tunnel in Sweden. In Hallandas village, Sweden, there is a case of cows and fish death caused by the acrylamide pollution resulted by the acrylamide that pumped to the surrounding soil [3].

In our country, Malaysia, large amounts of polyacrylamide are used annually for drinking water treatment. For instance, Kuching Water Board uses approximately 800kgs of polyacrylamide additive (Superfloc and Prestol 2530) yearly in the Sarawak state [4]. In agriculture field, acrylamide is introduced directly into agricultural soil via glyphosate application, where 20-30% polyacrylamide is added in commercial formulations as dispersing agent [5].

Research has shown that under environmental conditions, acrylamide is produced from polyacrylamide degradation and the half-life of acrylamide in soils and water bodies range from weeks to months [6]. In spite of well-known toxicity of acrylamide due to the acrylamide from the degradation of polyacrylamide and its presence as impurity in PAM, there is no investigation for acrylamide in the environment conducted by the Malaysian Department of Environment (DOE) and it is not part of the Interim National Quality Standards for Malaysia which listed maximum permit residual limits for aldrin, lindane, paraquat, chlordane, endosulfan and heptachlor.

There is no acrylamide allowed to be present in drinking water by the US EPA Primary Drinking Water Standards whilst, for the 2003 World Health Organisation (WHO), the allowable residual limits of acrylamide for the drinking water quality are at maximum of 0.10 µg/l [7]. Acrylamide is used as the main resin component in laminated wood and also often use in the plastic and printing production and from such industries, acrylamide can be found abundance as high as 1000 mg/L in the waste water according to Rogacheva and Ignatov [8]. As acrylamide is a neurotoxicant, has some carcinogenic and teratogenic activities its presence in the environment is a hazard and its remediation must be sought [2,9–11].

Acrylamide

The chemical formula of acrylamide is C_3H_5NO. Its other names include propenamide, acrylic amide, vinyl amide and 2-propenamide. Acrylamide is a compound which is widely used in industry to make polymeric substance that is utilized in numerous items. In its polymeric form it is called polyacrylamide, and is nontoxic compared to its monomeric form [12]. It has many uses in our everyday life [13]. It exists in either liquid or crystalline forms. The solid pure form is colorless to white. Acrylamide is soluble in dimethyl ether, water, methanol, ethanol, but is insoluble in benzene and heptane. The molecular mass of acrylamide is 71.08. its maximum solubility in water at 30°C is 2155 g/L. Its boiling and melting points are 125°C and 84.5°C, respectively at 1 atmospheric pressure [13]. The specific gravity of acrylamide at 30°C is 1.122 g/cm^3 [14].

Uses of acrylamide and polyacrylamide

Since the last century, acrylamide and its analogues have been used for many chemical and environmental purposes. The main or principle use of acrylamide is in the production of high molecular weight polyacrylamides which are customized to construct various compounds with different physical and chemical properties to suit the industrial needed. Up to 99.9% of acrylamide is estimated used in the polyacrylamide manufacture in Europe Union. Acrylamide is often utilized in both industrial sectors and medical laboratories since it is extremely reactive and water soluble. In the production of paper and pulp, the polymeric forms i.e. polyacrylamides are utilized as retention supports and as binders for fibres and also to enhance the preservation of pigments on the fibres. Acrylamide is also utilized to lower the erosion of soil, which its usage has been increasing over the years. Polyacrylamides is added onto the irrigation system to avert the deterioration of agricultural furrows, which can reduce as much as 94% of furrow erosion. [15].

In mines, great deal of acrylamide can be used on location to generate polyacrylamide gel which forms the grouting agent needed to seal mineshafts. Polyacrylamides are utilized as flocculants to separate solids from aqueous solutions. Additionally it is utilized in the removal of commercial waste materials and in the purifying of water resources [16]. Polyacrylamide permits a lot more concentrated sludge should they be utilized as dewatering or sludge conditioning materials and is more efficient than inorganic coagulants. The polymers form heavy aggregates when combining with particles and the resultant flocs rapidly settle out of solution as well as leaving a crystal-clear supernatant. The higher the molecular weight of the cationic polyacrylamide used, the more effective the polymer is [17]. In water treatment process acrylamide remains in the supernatant after flocculation with polyacrylamides, as acrylamide has high-water solubility and it tends to be inefficiently absorbed by sludge or sediment and sludge. The degradation of polyacrylamide is minima as the polymer is recalcitrant and at best only 10% will be degraded per year through physicochemical and biological actions [18–24].

There is not any data concerning the use of acrylamide and polyacrylamide obtainable in Malaysia to date; even there exists a range of industries in Malaysia which use polyacrylamide. The industrial sectors which use by far the most polyacrylamide is in the treatment of waste water, paper, and pulp processing. golf courses in Malaysia uses polyacrylamide to strengthen the foundation of the man-made ponds. This is the main route or cause for the toxic contamination of subterranean water which has triggered a number of poisoning and problems of the nervous system. Numerous golfer, caddies, as well as inhabitants have been discovered to experience irritations, skin illnesses as well as other hypersensitive symptoms [2,9,13,25,26]. In Malaysia, glyphosate in the commercial form of Roundup© is used for the control of a wide range of broad-leaved weeds and grasses in agricultural estate crops such as rubber, oil palm and cocoa [27–37] in the form of the glyphosate (Roundup™) formulation of which polyacrylamide is added as a dispersant and as a stabilizer (25-30% solutions). Estimated local usage gives rise to an estimated 2 million liters of polyacrylamide being dumped to the soil yearly and eventually runoffs into rivers and water bodies.

Acrylamide as pollutant

Industrially, acrylamide production uses a close system that allows very minimal pollution. This means that most of the pollution attributed to acrylamide comes from its uses in the mining, erosion control, tunneling works and agricultural sectors as herbicide's formulation or in the stabilization of agricultural soils. Due to this, acrylamide presence in the environment continues to be detected and its presence is being reported frequently nowadays [38–49].

The low vapor pressure of acrylamide coupled with its high-water solubility, makes it an uncommon source of air contaminant. Pollution of drinking-water by acrylamide is largely due to its use in the form of polyacrylamide flocculants of which acrylamide forms a significant residue [46]. Legislation has put a maximum acrylamide monomer in polyacrylamide for the use of potable water treatment at 0.05% (w/v) monomer. Acrylamide is stable in tap water for more than two months and will be present in drinking water. The recommended maximum permissible limit for drinking water for acrylamide in Malaysia is 0.0005 mg/L [50].

In the agricultural sector where polyacrylamide is combined with the herbicide glyphosate as additive (25% to 30% solutions) is the source of acrylamide pollutant in agricultural soils and irrigation and drainage systems [18–24]. It has been demonstrated that glyphosate formulation can be more toxic than glyphosate alone. Roundup has been found to be thirty times more toxic to fish than the compound glyphosate itself [51]. The depolymerisation of polyacrylamide to acrylamide, according to Smith *et al.* studies ,is strongly affected by light [52].

Toxicity of acrylamide

Acrylamide is toxic to the nervous system, carcinogen in laboratory animals, and also suspected to be carcinogen in humans [25]. In mouse, it has been shown that acrylamide binds to the DNA and mouse protamine at the spermiogenic stages and is suggested to cause genetic damage [53]. Acrylamide causes peripheral neurotoxicity, prenatal lethality, mutagenicity, clastogenicity, endocrine-related tumors and male reproductive toxicity in rodents, [26]. Yang *et al.* show the potential mutagenicity of acrylamide on *Salmonella* strains TA100 and TA98 [54]. An increase in the incidence of bone marrow's chromosomal aberrations is seen in mice exposed to acrylamide at dose of $\geq$ 50 mg/kg via intraperitoneal injection. Yet, in mice that subjected to acrylamide intraperitoneally at doses of up to 125 mg/kg shows no significant increases in the chromosomal aberrations frequency in the lymphocytes [55].

Acrylamide also affect male rat's reproductive system through causing several histopathological lesions in the seminiferous tubules. Human exposed to acrylamide via breathing the dust or absorption via skin, experience burning feeling or rash upon contact. Human's nervous system is affected which leads to weakness and numbness in the feet and hands, cause heavy sweating, imbalance and slurred tongue [25].

Due to its high-water solubility, acrylamide is absorbed through the lungs, intestinal tract, the placental barrier and the skin. A biomarker for acrylamide exposure is hemoglobin adducts which have been used to estimate the internal dose in the general population exposed to acrylamide though their occupations. At an acrylamide manufacturing plant, 41 workers exhibiting neurotoxicity index that are correlated with the acrylamide biomarker hemoglobin adducts [56]. In a China acrylamide manufacturing factory, hemoglobin adduct levels have been found to increase indicating a very high exposure to acrylamide [57]. In Japan, several cases of acute acrylamide poisoning due to a contamination of the water supply with acrylamide has been reported. Igisu *et al.* [58] reported that in a well-water where the waters are contaminated from a grouting operation 2.5 meters resulted in acrylamide levels as high as 400 mg acrylamide/L. Five people that ingested the contaminated water well experienced acrylamide toxicity such as confusion, memory disturbances, disorientation, hallucinations and truncal ataxia.

Acrylamide enters body via inhalation with contaminated air or consumed with contaminated food or water. Besides that, it also can be absorbed through unbroken skin, lungs and mucous membranes and the gastrointestinal tract. But it will not remain in the body because in will be removed with urine [39,44,45]. The acrylamide action's mechanism is greatly enhanced through its extensive allocation in body fluids and fairly even distribution throughout body organs. Even though acrylamide can be metabolized rapidly and excreted following exposure, the reason why it can possess hazards to workers and human is because of its high reactivity with proteins [59].

Degradation of polyacrylamide to acrylamide

Specific usages of acrylamide polymers and copolymers include as soil conditioners, flocculants in the dewatering and thickening of sludge, as bone cement binder and in sugar refinery [19,22,23]. It is estimated that in the United States alone a total of 25-50 million kilograms of polymer are utilized yearly. When acrylamide is released to the environment, depending on where the process occurs, acrylamide undergoes several of the degradation and removal processes producing the toxic acrylamide [48].

Bioremediation of acrylamide

Bioremediation is the use of plants or biologically active agents, microorganisms as a way to break down, sequester and conjugate ecological pollutants [60–70]. Usually the use of plants for this process is called phytoremediation. Certain microorganisms known to have the ability to degrade contaminants in the environment. Advantages of the bioremediation application include the easiness and timing of application and its ability to target specific pollutants. Besides that, bioremediation also can decrease sludge volume and ecological hazard. Even though the bioremediation is considered a new technology presently, the microorganisms have been used for no less than 100 years for the treatment and conversion of waste products.

There are three types of bioremediation predominant in the industry today; first of all is natural attenuation; secondly is biostimulation and the last one is called bioaugmentation. Natural attenuation is the simplest method of bioremediation. For this method, monitoring of the contaminated site for determining the levels of pollutants as a passive way to ensure regulators that the natural removal processes are ongoing. In biostimulation, an alteration to the site in the form of adding nutrients is required in order to boost the local population of the microorganism leading to an effective remediation of the contaminants. Nutrients that are usually added include nitrogen, phosphorus as well as trace elements. In addition, the adjustment of the soil's pH maybe necessary to make the site's pH suitable for the growth of the bioremediating microorganisms [60–70]. Lastly, bioaugmentation is another bioremediation approach where the absence of native communities due to the overwhelming presence of the hazardous contaminants is augmented or fortified with nonnative microorganisms to kick start the bioremediation process before local microorganisms that are accustomed to the soils conditions take over [60,71–76].

Acrylamide may contaminate groundwater as it is extremely mobile in aqueous environments. Acrylamide has a lower degradation rate in sandy soils than clay soils. Despite this, acrylamide degradation is water is considerably slower than soil [43]. Many species of microorganisms have the ability to degrade acrylamide under dark or light, aerobic or anaerobic conditions. To date numerous acrylamide-degrading microorganisms have been isolated and characterized [4,77–92] and some of the characteristics of these microorganisms is shown in **Table 1**. Many of these microorganisms can degrade aliphatic nitriles and amides and a majority found difficulty in degrading aromatic amides or nitriles.

Table 1. Acrylamide-degrading microorganisms.

Microorganism	Optimal conditions for growth	Other substrates	Ref.
Pseudomonas putida	pH 7.0 and 25 °C	Acetonitrile, glutaronitrile, butyronitrile, propionitrile, isobutyronitrile, methacrylonitrile, valeronitrile, succinonitrile, and amides such as butyramide, acetamide, propionamide, isobutyramide, succinamide and methacrylamide	[77]
Cupriavidus oxalaticus	pH 7.0 and 30 °C	Toerant to 60 mM (4,264 mg/L) acrylamide. Other amides such as formamide, acetamide, isobutyramide and urea (aliphatic amide), support growth while there was no activity on benzamide and nicotinamide (aromatic amide)	[92]
Rhodococcus sp.	pH 7.0 and 30°C	Acrylamide (62.8 mM or 4,463 mg/L) was supplied as the sole growth substrate. Can grow on aliphatic amides such as acetamide, butyramide, propionamide, and isobutyramide	[78]
Klebsiella pneumoniae	pH 7.5 and 28 °C	aliphatic nitriles containing 1 to 5 carbon atoms including acrylonitrile and aromatic nitriles such as benzonitrile as the sole source of nitrogen and propionamide and acetamide as the sole source of both nitrogen and carbon	[93]
Paracoccus sp.	pH 7.0 30 ºC	acetonitrile, aceylonitrile, propionitrile, valeronitrile, benzonitrile and the amides dimethylformamide, N,N-dimethylacetamide, N,N-dimethylfulfoxide, dimethylamine, methylamine, methanolamide, ethanolamide, acetamide, propionamide, valeramide, formamide, valeramide and acrylamide supported the growth of the culture with the release of ammonia, while aromatic amides did not support the growth of Paracoccus sp.	[94]

Table 1. Acrylamide-degrading microorganisms-continue.

Klebsiella pneumoniae NCTR 1	pH 7.2 and 30 °C	aliphatic amides such as acetamide, butyramide, methacrylamide, propionamide and succinamide) as the sole nitrogen source. Amidase enzyme is a monomer with an apparent molecular weight of 62,000. The temperature and pH for optimal enzyme activity were 65 °C and 7.0, respectively.	[79]
Rhodotorula sp. strain MBH23 KCTC 11960BP	between 27 and 30 °C and between pH 6.0 and 8.0	Tolerant acrylamide concentration is 1500 mg/L. Amides such as nicotinamide, 2-chloroacetamide, methacrylamide, propionamide and acetamide supported growth as nitrogen source. Growth inhibited by mercury, chromium, and cadmium	[95]
Pseudomonas sp. strain DRYJ7	At 15 °C and between pH 7.5 and 8.5.	Antarctic bacterium. Tolerant to 2500 mg/L acrylamide.	[4]
Bacillus cereus strain DRY135	between 25 and 30°C and between pH 6.8 and 7.0	Tolerable acrylamide concentration is 1500 mg/L. Can grow on other amides such as nicotinamide, methacrylamide, propionamide, acetamide and urea. Cannot grow on 2-chloroacetamide.	[4]
Burkholderia sp. strain DR.Y27	between pH 6.0 and 8.0. and at 30°C	Can grow on aliphatic amides such as 2-chloroacetamide, nicotinamide, methacrylamide, propionamide, acetamide and urea	[96]

REFERENCE

1. Myagchenkov VA, Proskurina VE. Kinetics of flocculation and densification in ocher suspension in the presence of polyacrylamide, poly(ethylene oxide), and their 1 : 1 mixture. Colloid J Russ Acad Sci Kolloidn Zhurnal. 2000;62(5):588–93.
2. Shipp A, Lawrence G, Gentry R, McDonald T, Bartow H, Bounds J, et al. Acrylamide: review of toxicity data and dose-response analyses for cancer and noncancer effects. Crit Rev Toxicol. 2006;36(6–7):481–608.
3. Franzen T, Garshol KF, Tomisawa N. Sprayed concrete for final linings: ITA working group report. Tunn Undergr Space Technol. 2001;16(4):295–309.
4. Shukor A, Yunus M, Gusmanizar N, Ramli J, Shamaan NA, MacCormack W, et al. Isolation and characterization of an acrylamide-degrading Antarctic bacterium. J Environ Biol. 2009;30(1):107–112.
5. Dinehart SK, Smith LM, McMurry ST, Anderson TA, Smith PN, Haukos DA. Toxicity of a glufosinate- and several glyphosate-based herbicides to juvenile amphibians from the Southern High Plains, USA. Sci Total Environ. 2009;407(3):1065–71.
6. Brown L, Rhead MM, Bancroft KCC, Allen N. Model studies of the degradation of acrylamide monomer. Water Res. 1980;14(7):775–8.
7. Guezennec AG, Michel C, Bru K, Touze S, Desroche N, Mnif I, et al. Transfer and degradation of polyacrylamide-based flocculants in hydrosystems: A review. Environ Sci Pollut Res. 2015;22(9):6390–406.
8. Rogacheva SM, Ignatov OV. The respiratory activity of *Rhodococcus rhodochrous* M8 cells producing nitrile-hydrolyzing enzymes. Appl Biochem Microbiol. 2001;37(3):282–6.
9. Barber DS, Hunt JR, Ehrich MF, Lehning EJ, LoPachin RM. Metabolism, toxicokinetics and hemoglobin adduct formation in rats following subacute and subchronic acrylamide dosing. NeuroToxicology. 2001;22(3):341–53.
10. Wang C-C, Lee C-M. Isolation of the acrylamide denitrifying bacteria from a wastewater treatment system manufactured with polyacrylonitrile fiber. Curr Microbiol. 2007;55(4):339–43.
11. Gupte S, Keharia H, Gupte A. Toxicity analysis of azo Red BS and Methyl Red dye solutions on earthworm (*Pheretima phosthuma*), micro-organisms, and plants. Desalination Water Treat. 2013;51(22–24):4556–65.
12. Silva MESR e, Dutra ER, Mano V, Machado JC. Preparation and thermal study of polymers derived from acrylamide. Polym Degrad Stab. 2000 Mar 1;67(3):491–5.
13. Friedman M. Chemistry, Biochemistry, and Safety of Acrylamide. A Review. J Agric Food Chem. 2003 Jul 1;51(16):4504–26.
14. Stadler RH, Blank I, Varga N, Robert F, Hau J, Guy PA, et al. Acrylamide from Maillard reaction products. Nature. 2002 Oct;419(6906):449–50.
15. Kay-Shoemake JL, Watwood ME, Lentz RD, Sojka RE. Polyacrylamide as an organic nitrogen source for soil microorganisms with potential effects on inorganic soil nitrogen in agricultural soil. Soil Biol Biochem. 1998;30(8–9):1045–52.
16. Park JH, Oh C, Han Y-S, Ji S-W. Optimizing the addition of flocculants for recycling mineral-processing wastewater. Geosystem Eng. 2016 Mar 3;19(2):83–8.
17. Yu X, Somasundaran P. Enhanced flocculation with double flocculants. Colloids Surf Physicochem Eng Asp. 1993 Dec 13;81:17–23.
18. Sojka RE, Lentz RD, Ross CW, Trout TJ, Bjorneberg DL, Aase JK. Polyacrylamide effects on infiltration in irrigated agriculture. J Soil Water Conserv. 1998;53(4):325–31.
19. Sojka RE, Bjorneberg DL, Entry JA, Lentz RD, Orts WJ. Polyacrylamide in Agriculture and Environmental Land Management. 2007. 75 p. (Advances in Agronomy; vol. 92).
20. Lentz RD. Inhibiting water infiltration with polyacrylamide and surfactants: Applications for irrigated agriculture. J Soil Water Conserv. 2003;58(5):290–300.
21. Lentz RD. Inhibiting water infiltration into soils with cross-linked polyacrylamide: Seepage reduction for irrigated agriculture. Soil Sci Soc Am J. 2007;71(4):1352–62.
22. Petersen AL, Thompson AM, Baxter C, Norman JM, Roa-Espinosa A. A new polyacrylamide (PAM) formulation for reducing erosion and phosphorus loss in rainfed agriculture. Trans ASABE. 2007;50(6):2091–101.
23. Weston DP, Lentz RD, Cahn MD, Ogle RS, Rothert AK, Lydy MJ. Toxicity of anionic polyacrylamide formulations when used for erosion control in agriculture. J Environ Qual. 2009;38(1):238–47.
24. Freitas JS, de Oliveira LFC, Abreu ECF, Almeida AES. Photodegradation of polyacrylamide hydrogel in the presence of chemical substances for use in agriculture. Rev Mater. 2019;24(3).
25. Spencer P, Schaumburg HH. Nervous system degeneration produced by acrylamide monomer. Environ Health Perspect. 1975 Jun 1;11:129–33.
26. Tyl RW, Friedman MA. Effects of acrylamide on rodent reproductive performance. Reprod Toxicol. 2003 Jan 1;17(1):1–13.
27. Lee LJ, Ngim J. A first report of glyphosate-resistant goosegrass (Eleusine indica (L) Gaertn) in Malaysia. Pest Manag Sci. 2000;56(4):336–9.
28. Baerson SR, Rodriguez DJ, Tran M, Feng Y, Biest NA, Dill GM. Glyphosate-resistant goosegrass. Identification of a mutation in the target enzyme 5-enolpyruvylshikimate-3-phosphate synthase. Plant Physiol. 2002;129(3):1265–75.
29. Ng CH, Wickneswari R, Salmijah S, Teng YT, Ismail BS. Gene polymorphisms in glyphosate-resistant and -susceptible biotypes of Eleusine indica from Malaysia. Weed Res. 2003;43(2):108–15.
30. Ng CH, Wickneswary R, Salmijah S, Teng YT, Ismail BS. Glyphosate resistance in Eleusine indica (L.) Gaertn. from different origins and polymerase chain reaction amplification of specific alleles. Aust J Agric Res. 2004;55(4):407–14.
31. Mardiana-Jansar K, Ismail BS. Residue determination and levels of glyphosate in surface waters, sediments and soils associated with oil palm plantation in tasik chini, pahang, malaysia. In 2014. p. 795–802.
32. Raven M. On American politics, African trade, companies, migrants, glyphosate, Malaysia, the semicolon: Letters to the editor. Econ U K. 2016;412(8978).
33. Chen J, Jiang C, Huang H, Wei S, Huang Z, Wang H, et al. Characterization of Eleusine indica with gene mutation or amplification in EPSPS to glyphosate. Pestic Biochem Physiol. 2017;143:201–6.
34. Manogaran M, Shukor MY, Yasid NA, Johari WLW, Ahmad SA. Isolation and characterisation of glyphosate-degrading bacteria isolated from local soils in Malaysia. Rendiconti Lincei. 2017;28(3):471–9.

35. Salgado TP, Pereira FCM, Alves PLCA, Kuva MA. Effects of glyphosate on growth, yield and wood quality of eucalyptus urograndis. J Trop For Sci. 2017;29(3):257–66.
36. Garba J, Samsuri AW, Othman R, Ahmad Hamdani MS. Adsorption-desorption and leaching potential of glyphosate and aminomethylphosphonic acid in acidic Malaysian soil amended with cow dung and rice husk ash. Environ Monit Assess. 2018;190(11).
37. Rahman F, Ismail A, Yusof S, Mazlan N, Engku-Ahmad-Khairi E-A. Evaluation of glyphosate levels in sediments of milky stork foraging areas in Kuala Gula Bird Sanctuary, Perak, Malaysia. Pertanika J Trop Agric Sci. 2019;42(3):995–1007.
38. Weideborg M, Källqvist T, Ødegård KE, Sverdrup LE, Vik EA. Environmental risk assessment of acrylamide and methylolacrylamide from a grouting agent used in the tunnel construction of romeriksporten, Norway. Water Res. 2001;35(11):2645–52.
39. Eikmann T, Herr C. How dangerous is actually acrylamide exposure for the population. Umweltmed Forsch Prax. 2002;7(6):307–8.
40. Güven KC, Gezgin T. Determination of acrylonitrile and detection of acrylamide in seawater by GC/MS. Acta Pharm Turc. 2005;47(1):15–20.
41. Lentz RD, Andrawes FF, Barvenik FW, Koehn AC. Acrylamide monomer leaching from polyacrylamide-treated irrigation furrows. J Environ Qual. 2008;37(6):2293–8.
42. Heudorf U, Hartmann E, Angerer J. Acrylamide in children - exposure assessment via urinary acrylamide metabolites as biomarkers. Int J Hyg Environ Health. 2009;212(2):135–41.
43. Paz-Alberto AM, de Dios MJJ, Alberto RT, Sigua GC. Assessing phytoremediation potentials of selected tropical plants for acrylamide. J Soils Sediments. 2011;11(7):1190–8.
44. Pruser KN, Flynn NE. Acrylamide in health and disease. Front Biosci - Sch. 2011;3 S(1):41–51.
45. Pennisi M, Malaguarnera G, Puglisi V, Vinciguerra L, Vacante M, Malaguarnera M. Neurotoxicity of acrylamide in exposed workers. Int J Environ Res Public Health. 2013;10(9):3843–54.
46. Touzé S, Guerin V, Guezennec A-G, Binet S, Togola A. Dissemination of acrylamide monomer from polyacrylamide-based flocculant use—sand and gravel quarry case study. Environ Sci Pollut Res. 2015;22(9):6423–30.
47. Mojska H, Gielecińska I, Cendrowski A. Acrylamide content in cigarette mainstream smoke and estimation of exposure to acrylamide from tobacco smoke in Poland. Ann Agric Environ Med. 2016;23(3):456–61.
48. Nunes BW, Hedlund KF, Oliveira MA, Carissimi E. Ecotoxicological analysis of acrylamide using a microalga as an indicator organism. Water Environ Res. 2018;90(5):442–51.
49. Radwan MA, El-Gendy KS, Gad AF, Khamis AE, Eshra E-SH. Ecotoxicological biomarkers as investigating tools to evaluate the impact of acrylamide on Theba pisana snails. Environ Sci Pollut Res. 2019;
50. Engineering of Services Division. NDWQS: National Drinking Water Quality Standard. 2nd ed. Kuala Lumpur, Malaysia: Ministry of Health Malaysi; 2004.
51. Servizi JA, Gordon RW, Martens DW. Acute toxicity of Garlon 4 and Roundup herbicides to Salmon,Daphnia, and trout. Bull Environ Contam Toxicol. 1987 Jul 1;39(1):15–22.
52. Smith EA, Prues SL, Oehme FW. Environmental degradation of polyacrylamides. 1. Effects of artificial environmental conditions: Temperature, light, and pH. Ecotoxicol Environ Saf. 1996;35(2):121–35.
53. Sega GA, Valdivia Alcota RP, Tancongco CP, Brimer PA. Acrylamide binding to the DNA and protamine of spermiogenic stages in the mouse and its relationship to genetic damage. Mutat Res Mutagen Relat Subj. 1989 Aug 1;216(4):221–30.
54. Yang H-J, Lee S-H, Jin Y, Choi J-H, Han C-H, Lee M-H. Genotoxicity and toxicological effects of acrylamide on reproductive system in male rats. J Vet Sci. 2005 Jun;6(2):103–9.
55. Backer LC, Dearfield KL, Erexson GL, Campbell JA, Westbrook-Collins B, Allen JW. The effects of acrylamide on mouse germ-line and somatic cell chromosomes. Environ Mol Mutagen. 1989;13(3):218–26.
56. Calleman CJ, Wu Y, He F, Tian G, Bergmark E, Zhang S, et al. Relationships between Biomarkers of Exposure and Neurological Effects in a Group of Workers Exposed to Acrylamide. Toxicol Appl Pharmacol. 1994 Jun 1;126(2):361–71.
57. Hagmar L, Törnqvist M, Nordander C, Rosén I, Bruze M, Kautiainen A, et al. Health effects of occupational exposure to acrylamide using hemoglobin adducts as biomarkers of internal dose. Scand J Work Environ Health. 2001;27(4):219–26.
58. Igisu H, Goto I, Kawamura Y, Kato M, Izumi K. Acrylamide encephaloneuropathy due to well water pollution. J Neurol Neurosurg Psychiatry. 1975;38(6):581–4.
59. Cavins JF, Friedman M. Specific modification of protein sulfhydryl groups with alpha,beta-unsaturated compounds. J Biol Chem. 1968;243(12):3357–60.
60. Plangklang P, Reungsang A. Bioaugmentation of carbofuran residues in soil by *Burkholderia cepacia* PCL3: A small-scale field study. Int Biodeterior Biodegrad. 2011;65(6):902–5.
61. Udikoviç-Koliç N, Scott C, Martin-Laurent F. Evolution of atrazine-degrading capabilities in the environment. Appl Microbiol Biotechnol. 2012;96(5):1175–89.
62. Hussain S, Maqbool Z, Ali S, Yasmeen T, Imran M, Mahmood F, et al. Biodecolorization of reactive black-5 by a metal and salt tolerant bacterial strain *Pseudomonas* sp. RA20 isolated from Paharang drain effluents in Pakistan. Ecotoxicol Environ Saf. 2013;98:331–8.
63. Masciandaro G, Macci C, Peruzzi E, Ceccanti B, Doni S. Organic matter-microorganism-plant in soil bioremediation: A synergic approach. Rev Environ Sci Biotechnol. 2013;12(4):399–419.
64. Hadibarata T, Kristanti RA. Fluorene biodegradation and identification of transformation products by white-rot fungus *Armillaria* sp. F022. Biodegradation. 2014;25(3):373–82.
65. Al-Musharafi SK. Heavy metals in sewage treated effluents: Pollution and microbial bioremediation from arid regions. Open Biotechnol J. 2016;10:352–62.
66. Andreolli M, Albertarelli N, Lampis S, Brignoli P, Khoei NS, Vallini G. Bioremediation of diesel contamination at an underground storage tank site: a spatial analysis of the microbial community. World J Microbiol Biotechnol. 2016;32(1):1–12.
67. Santaeufemia S, Torres E, Mera R, Abalde J. Bioremediation of oxytetracycline in seawater by living and dead biomass of the microalga Phaeodactylum tricornutum. J Hazard Mater. 2016;320:315–25.
68. Ortíz-Maya J, Escalante-Espinosa E, Fócil-Monterrubio RL, Ramírez-Saad HC, Díaz Ramírez IJ. Dynamics of bacterial populations and dehydrogenase activity during bioremediation of newly contaminated and weathered soil with hydrocarbons. Rev Int Contam Ambient. 2017;33(2):237–46.
69. Sánchez-Castro I, Amador-García A, Moreno-Romero C, López-Fernández M, Phrommavanh V, Nos J, et al. Screening of bacterial strains isolated from uranium mill tailings porewaters for bioremediation purposes. J Environ Radioact. 2017;166:130–41.
70. Yakasai MH, Rahman MFA, Rahim MBHA, Khayat ME, Shamaan NA, Shukor MY. Isolation and characterization of a metal-reducing *Pseudomonas* sp. strain 135 with amide-degrading capability. Bioremediation Sci Technol Res. 2017;5(2):32–38.
71. Ruberto LAM, Vazquez S, Lobalbo A, Mac Cormack WP. Psychrotolerant hydrocarbon-degrading *Rhodococcus* strains isolated from polluted Antarctic soils. Antarct Sci. 2005;17(1):47–56.
72. Guo Q, Wan R, Xie S. Simazine degradation in bioaugmented soil: Urea impact and response of ammonia-oxidizing bacteria and other soil bacterial communities. Environ Sci Pollut Res. 2014;21(1):337–43.
73. Kristanti RA, Toyama T, Hadibarata T, Tanaka Y, Mori K. Bioaugmentation involving a bacterial consortium isolated from the rhizosphere of *Spirodela polyrhiza* for treating water contaminated with a mixture of four nitrophenol isomers. RSC Adv. 2014;4(4):1616–21.
74. Krüger US, Johnsen AR, Burmølle M, Aamand J, Sørensen SR. The potential for bioaugmentation of sand filter materials from waterworks using bacterial cultures degrading 4-chloro-2-methylphenoxyacetic acid. Pest Manag Sci. 2015;71(2):257–65.
75. Mannucci A, Munz G, Mori G, Makinia J, Lubello C, Oleszkiewicz JA. Modeling bioaugmentation with nitrifiers in membrane bioreactors. Water Sci Technol. 2015;71(1):15–21.

76. Castro-Gutiérrez V, Masís-Mora M, Carazo-Rojas E, Mora-López M, Rodríguez-Rodríguez CE. Impact of oxytetracycline and bacterial bioaugmentation on the efficiency and microbial community structure of a pesticide-degrading biomixture. Environ Sci Pollut Res. 2018;25(12):11787–99.
77. Nawaz MS, Chapatwala KD, Wolfram JH. Degradation of acetonitrile by *Pseudomonas putida*. Appl Environ Microbiol. 1989;55(9):2267–74.
78. Nawaz MS, Khan AA, Seng JE, Leakey JE, Siitonen PH, Cerniglia CE. Purification and characterization of an amidase from an acrylamide- degrading *Rhodococcus* sp. Appl Environ Microbiol. 1994;60(9):3343–8.
79. Nawaz MS, Khan AA, Bhattacharayya D, Siitonen PH, Cerniglia CE. Physical, biochemical, and immunological characterization of a thermostable amidase from *Klebsiella pneumoniae* NCTR 1. J Bacteriol. 1996;178(8):2397–401.
80. Silman NJ, Carver MA, Jones CW. Directed evolution of amidase in *Methylophilus methylotrophus*; purification and properties of amidases from wild-type and mutant strains. J Gen Microbiol. 1991;137(1):169–78.
81. Sathesh Prabu C, Thatheyus AJ. Biodegradation of acrylamide employing free and immobilized cells of *Pseudomonas aeruginosa*. Int Biodeterior Biodegrad. 2007;60(2):69–73.
82. Galai S, Limam F, Marzouki MN. A new *Stenotrophomonas maltophilia* strain producing laccase. use in decolorization of synthetics dyes. Appl Biochem Biotechnol. 2009;158(2):416–31.
83. Buranasilp K, Charoenpanich J. Biodegradation of acrylamide by *Enterobacter aerogenes* isolated from wastewater in Thailand. J Environ Sci. 2011;23(3):396–403.
84. Cha M, Chambliss GH. Characterization of acrylamidase isolated from a newly isolated acrylamide-utilizing bacterium, *Ralstonia eutropha* AUM-01. Curr Microbiol. 2011;62(2):671–8.
85. Syed MA, Ahmad SA, Kusnin N, Shukor MYA. Purification and characterization of amidase from acrylamide-degrading bacterium *Burkholderia* sp. strain DR.Y27. Afr J Biotechnol. 2012;11(2):329–36.
86. Thanyacharoen U, Tani A, Charoenpanich J. Isolation and characterization of *Kluyvera georgiana* strain with the potential for acrylamide biodegradation. J Environ Sci Health - Part ToxicHazardous Subst Environ Eng. 2012;47(11):1491–9.
87. Emmanuel Joshua Jebasingh S, Lakshmikandan M, Rajesh RP, Raja P. Biodegradation of acrylamide and purification of acrylamidase from newly isolated bacterium *Moraxella osloensis* MSU11. Int Biodeterior Biodegrad. 2013;85:120–5.
88. c CJ a b, A.d T. Proteome analysis of acrylamide-induced proteins in a novel acrylamide-degrader *Enterobacter aerogenes* by 2D electrophoresis and MALDI-TOF-MS. Chiang Mai Univ J Nat Sci. 2014;13(1):11–22.
89. Mansur R, Gusmanizar N, Dahalan FA, Masdor NA, Ahmad SA, Shukor MS, et al. Isolation and characterization of a molybdenum-reducing and amide-degrading *Burkholderia cepacia* strain neni-11 in soils from west Sumatera, Indonesia. IIOAB. 2016;7(1):28–40.
90. Rahman MFA, Yasid NA, Ahmad SA, Shamaan NA, Shukor MY. Characterization of molybdenum-reduction by an acrylamide-degrading Antarctic bacterium. In 10-3 Midori-cho, Tachikawa, Tokyo, Japan: National Institute of Polar Research (NIPR); 2018. Available from: http://id.nii.ac.jp/1291/00015258/
91. Kesavan V, Mansur A, Suhaili Z, Salihan MSR, Rahman MFA, Shukor MY. Isolation and Characterization of a Heavy Metal-reducing *Pseudomonas* sp. strain Dr.Y Kertih with the Ability to Assimilate Phenol and Diesel. Bioremediation Sci Technol Res. 2018 Jul 31;6(1):14–22.
92. Bedade DK, Singhal RS. Biodegradation of acrylamide by a novel isolate, *Cupriavidus oxalaticus* ICTDB921: Identification and characterization of the acrylamidase produced. Bioresour Technol. 2018 Aug 1;261:122–32.
93. Nawaz MS, Franklin W, Campbell WL, Heinze TM, Cerniglia CE. Metabolism of acrylonitrile by *Klebsiella pneumoniae*. Arch Microbiol. 1991 Aug 1;156(3):231–8.
94. Santoshkumar M, Veeranagouda Y, Lee K, Karegoudar TB. Utilization of aliphatic nitrile by *Paracoccus* sp. SKG isolated from chemical waste samples. Int Biodeterior Biodegrad. 2011;65(1):153–9.
95. Rahim MBH, Syed MA, Shukor MY. Isolation and characterization of an acrylamide-degrading yeast *Rhodotorula* sp. strain MBH23 KCTC 11960BP. J Basic Microbiol. 2012;52(5):573–81.
96. Gusmanizar N, Shukor Y, Ramli J, Syed MA. Isolation and characterization of an acrylamide-degrading *Burkholderia* sp. strain DR.Y27. J Ris Kim. 2015 Feb 11;2(1):34.