

# Transport and release of chemicals from plastics to the environment and to wildlife

Teuten E.L., Saquing J.M., Knappe D.R.U., Barlaz M.A., Jonsson S., Bjorn A., Rowland S.J., Thompson R.C., Galloway T.S., Yamashita R., Ochi D., Watanuki Y., Moore C., Viet P.H., Tana T.S., Prudente M., Boonyatumanond R., Zakaria M.P., Akkhavong K., Ogata Y., Hirai H., Iwasa S., Mizukawa K., Hagino Y., Imamura A., Saha M., Takada H.

Marine Biology and Ecology Research Centre, Marine Institute, University of Plymouth, A403 Portland Square, Drake Circus, Plymouth PL4 8AA, United Kingdom; School of Engineering and Electronics, University of Edinburgh, Old College, South Bridge Edinburgh EH8 9YL, United Kingdom; Department of Civil, Construction and Environmental Engineering, North Carolina State University, PO Box 7908, Raleigh, NC 27695, United States; Department of Water and Environmental Studies, Linköping University, SE-581 83, Linköping, Sweden; Marine Biology and Ecology Research Centre, Marine Institute, University of Plymouth, Drake Circus, Plymouth PL4 8AA, United Kingdom; School of Biosciences, University of Exeter, Stocker Road, Exeter, EX4 4QD, United Kingdom; Graduate School of Fisheries, Hokkaido University, Hakodate, Hokkaido 041-8611, Japan; Algalita Marine Research Foundation, 148 Marina Drive Long Beach, CA 90803, United States; Research Centre for Environmental Technology and Sustainable Development (CETASD), Hanoi University of Science, Vietnam National University, 334 Nguyen Trai Street, Thanh Xuan District, Hanoi, Viet Nam; Economic, Social and Cultural Observation Unit, Office of the Council of Minister, Sahapoon Russi Blvd., Phnom Penh, Cambodia; Science Education Department, De La Salle University, 2401 Taft Avenue, Malate, 1004 Manila, Philippines; Environmental Research and Training Center, Bangkok, Technopolis, Klong 5, Klong Luang, Pathumthani 12120, Thailand; Department of Environmental Sciences, Faculty of Environmental Studies, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor Darul Ehsan, Malaysia; National Institute of Public Health, Samsenthai road, Ban Kao-Gnod, Sisattanak District, Vientiane Municipality, Democratic Republic Congo; Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan

**Abstract:** Plastics debris in the marine environment, including resin pellets, fragments and microscopic plastic fragments, contain organic contaminants, including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, petroleum hydrocarbons, organochlorine pesticides (2,2'-bis(p-chlorophenyl)-1,1,1-trichloroethane, hexachlorinated hexanes), polybrominated diphenylethers, alkylphenols and bisphenol A, at concentrations from sub ng g<sup>-1</sup> to µg g<sup>-1</sup>. Some of these compounds are added during plastics manufacture, while others adsorb from the surrounding seawater. Concentrations of hydrophobic contaminants adsorbed on plastics showed distinct spatial variations reflecting global pollution patterns. Model calculations and experimental observations consistently show that polyethylene accumulates more organic contaminants than other plastics such as polypropylene and polyvinyl chloride. Both a mathematical model using equilibrium partitioning and experimental data have demonstrated the transfer of contaminants from plastic to organisms. A feeding experiment indicated that PCBs could transfer from contaminated plastics to streaked shearwater chicks. Plasticizers, other plastics additives and constitutional monomers also present potential threats in terrestrial environments because they can leach from waste disposal sites into groundwater and/or

surfacewaters. Leaching and degradation of plasticizers and polymers are complex phenomena dependent on environmental conditions in the landfill and the chemical properties of each additive. Bisphenol A concentrations in leachates from municipal waste disposal sites in tropical Asia ranged from  $\text{sub } \mu\text{g l}^{-1}$  to  $\mu\text{g l}^{-1}$  and were correlated with the level of economic development. © 2009 The Royal Society.

Author Keywords: Endocrine-disrupting chemicals; Landfill leachate; Marine plastic debris; Microplastics; Persistent organic pollutants; Plastic resin pellet

Index Keywords: 4,4' isopropylidenediphenol; diphenyl ether derivative; endocrine disruptor; pesticide; petroleum; phenol derivative; plastic; polychlorinated biphenyl; polycyclic aromatic hydrocarbon; sea water; concentration (composition); endocrine disruptor; environmental conditions; landfill; leaching; marine pollution; numerical model; organic pollutant; PAH; PCB; plastic waste; resin; spatial variation; waste disposal; waste facility; wildlife management; adsorption; animal; article; bird; chemistry; feeding behavior; food chain; kinetics; metabolism; physiology; pollutant; pollution; Polychaeta; theoretical model; Adsorption; Animals; Birds; Endocrine Disruptors; Environmental Pollutants; Feeding Behavior; Food Chain; Halogenated Diphenyl Ethers; Kinetics; Models, Theoretical; Pesticides; Petroleum; Phenols; Plastics; Polychaeta; Polychlorinated Biphenyls; Polycyclic Hydrocarbons, Aromatic; Seawater; Waste Products

Year: 2009

Source title: Philosophical Transactions of the Royal Society B: Biological Sciences

Volume: 364

Issue: 1526

Page : 2027-2045

Cited by: 18

Link: Scopus Link

Chemicals/CAS: 4,4' isopropylidenediphenol, 80-05-7; petroleum, 8002-05-9; Endocrine Disruptors; Environmental Pollutants; Halogenated Diphenyl Ethers; Pesticides; Petroleum; Phenols; Plastics; Polychlorinated Biphenyls; Polycyclic Hydrocarbons, Aromatic; Waste Products; bisphenol A, 80-05-7

Correspondence Address: Takada, H.; Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan; email: shige@cc.tuat.ac.jp

ISSN: 9628436

CODEN: PTRBA

DOI: 10.1098/rstb.2008.0284

PubMed ID: 19528054

Language of Original Document: English

Abbreviated Source Title: Philosophical Transactions of the Royal Society B: Biological Sciences

Document Type: Article

Source: Scopus

Authors with affiliations:

- Teuten, E.L., Marine Biology and Ecology Research Centre, Marine Institute, University of Plymouth, A403 Portland Square, Drake Circus, Plymouth PL4 8AA, United Kingdom, School of Engineering and Electronics, University of Edinburgh, Old College, South Bridge Edinburgh EH8 9YL, United Kingdom

- Saquing, J.M., Department of Civil, Construction and Environmental Engineering, North Carolina State University, PO Box 7908, Raleigh, NC 27695, United States
- Knappe, D.R.U., Department of Civil, Construction and Environmental Engineering, North Carolina State University, PO Box 7908, Raleigh, NC 27695, United States
- Barlaz, M.A., Department of Civil, Construction and Environmental Engineering, North Carolina State University, PO Box 7908, Raleigh, NC 27695, United States
- Jonsson, S., Department of Water and Environmental Studies, Linköping University, SE-581 83, Linköping, Sweden
- Björn, A., Department of Water and Environmental Studies, Linköping University, SE-581 83, Linköping, Sweden
- Rowland, S.J., Marine Biology and Ecology Research Centre, Marine Institute, University of Plymouth, Drake Circus, Plymouth PL4 8AA, United Kingdom
- Thompson, R.C., Marine Biology and Ecology Research Centre, Marine Institute, University of Plymouth, A403 Portland Square, Drake Circus, Plymouth PL4 8AA, United Kingdom
- Galloway, T.S., School of Biosciences, University of Exeter, Stocker Road, Exeter, EX4 4QD, United Kingdom
- Yamashita, R., Graduate School of Fisheries, Hokkaido University, Hakodate, Hokkaido 041-8611, Japan
- Ochi, D., Graduate School of Fisheries, Hokkaido University, Hakodate, Hokkaido 041-8611, Japan
- Watanuki, Y., Graduate School of Fisheries, Hokkaido University, Hakodate, Hokkaido 041-8611, Japan
- Moore, C., Algalita Marine Research Foundation, 148 Marina Drive Long Beach, CA 90803, United States
- Viet, P.H., Research Centre for Environmental Technology and Sustainable Development (CETASD), Hanoi University of Science, Vietnam National University, 334 Nguyen Trai Street, Thanh Xuan District, Hanoi, Viet Nam
- Tana, T.S., Economic, Social and Cultural Observation Unit, Office of the Council of Minister, Sahapoan Russi Blvd., Phnom Penh, Cambodia
- Prudente, M., Science Education Department, De La Salle University, 2401 Taft Avenue, Malate, 1004 Manila, Philippines
- Boonyatumanond, R., Environmental Research and Training Center, Bangkok, Technopolis, Klong 5, Klong Luang, Pathumthani 12120, Thailand
- Zakaria, M.P., Department of Environmental Sciences, Faculty of Environmental Studies, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor Darul Ehsan, Malaysia
- Akkhavong, K., National Institute of Public Health, Samsenthai road, Ban Kao-Gnod, Sisattanak District, Vientiane Municipality, Democratic Republic Congo
- Ogata, Y., Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan
- Hirai, H., Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan
- Iwasa, S., Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan
- Mizukawa, K., Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan
- Hagino, Y., Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan
- Imamura, A., Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan
- Saha, M., Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-

8509, Japan

- Takada, H., Laboratory of Organic Geochemistry (LOG), Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan

## References:

- Ahrens, M.J., Hertz, J., Lamoureux, E.M., Lopez, G.R., McElroy, A.E., Brownawell, B.J., The role of digestive surfactants in determining bioavailability of sediment-bound hydrophobic organic contaminants to 2 deposit-feeding polychaetes (2001) *Mar. Ecol. Prog. Ser.*, 212, pp. 145-157. , doi:10.3354/meps212145
- Ali, L.N., Mantoura, R.F., Rowland, S.J., The dissolution and photodegradation of Kuwaiti crude oil in seawater. Part 2: A laboratory photodegradation apparatus and photodegradation kinetics of a model seawater soluble hydrocarbon (phenanthrene) (1995) *Mar. Environ. Res.*, 40, pp. 319-335. , doi:10.1016/0141-1136(94)00149-J
- Asakura, H., Matsuto, T., Tanaka, N., Behavior of endocrine-disrupting chemicals in leachate from MWS landfill sites in Japan (2004) *Waste Manag.*, 24, pp. 613-622. , doi:10.1016/j.wasman.2004.02.004
- Baird, R.W., Hooker, S.K., Ingestion of plastic and unusual prey by a juvenile porpoise (2000) *Mar. Pollut. Bull.*, 40, pp. 719-720. , doi:10.1016/S0025-326X(00)00051-5
- Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., Accumulation and fragmentation of plastic debris in global environments (2009) *Phil. Trans. R. Soc. B.*, 364, pp. 1985-1998. , doi:10.1098/rstb.2008.0205
- Batt, J.M., (2006) The world of organotin chemicals: Applications, substituents, and the environment, , <http://ortepa.org/WorldofOrganotinChemicals.pdf>, Organotin Environmental Program Association ORTEPA, See
- Bauer, M.J., Herrmann, R., Dissolved organic carbon as the main carrier of phthalic acid esters in municipal landfill leachates (1998) *Waste Manag. Res.*, 16, pp. 446-454. , doi:10.1177/0734242X9801600507
- Bauer, M.J., Hermann, R., Martin, A., Zellmann, H., Chemodynamics, transport behaviour and treatment of phthalic acid esters in municipal landfill leachates (1998) *Water Sci. Technol.*, 38, pp. 185-192
- Berens, A.R., Sorption of organic liquids and vapors by rigid PVC (1989) *J. Appl. Polym. Sci.*, 37, pp. 901-913. , doi:10.1002/app.1989.070370405
- Björn, A., Microbial transformation of organotin compounds under simulated landfill conditions (Diss.) (2007) *Linköping Studies in Arts and Science*, (415). , Linköping University, Sweden
- Björn, A., Hörsing, M., Karlsson, A., Mersiowsky, I., Ejlertsson, J., Impacts of temperature on the leaching of organotin compounds from poly(vinyl chloride) plastics - a study conducted under simulated landfill conditions (2007) *J. Vinyl Addit. Technol.*, 13, pp. 176-188. , doi:10.1002/vnl.20131
- Boyer, R.F., Relation of tensile strength to brittle temperature in plasticized polymers (1951) *J. Appl. Phys.*, 12, pp. 723-728
- Brandup, J., Immergut, E.H., Grulke, E.A., (1989) *Polymer handbook*, p. 206. , New York, NY: Wiley
- Brusseau, M.L., Jessup, R.E., Rao, P.S.C., Nonequilibrium sorption of organic chemicals: Elucidation of rate-limiting processes (1991) *Environ. Sci. Technol.*, 25, pp. 134-142. , doi:10.1021/es00013a015
- Cadée, G.C., Seabirds and floating plastic debris (2002) *Mar. Pollut. Bull.*, 44, pp. 1294-1295. , doi:10.1016/S0025-326X(02)00264-3
- Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B., Polystyrene spherules in coastal waters (1972) *Science*, 178, pp. 749-750. , doi:10.1126/science.178.4062.749
- Carter, M.C., Kilduff, J.E., Weber, W.J., Site energy distribution analysis of preloaded adsorbents (1995) *Environ. Sci. Technol.*, 29, pp. 1773-1780. , doi:10.1021/es00007a013
- Chiou, C.T., Kile, D.E., Deviations from sorption linearity on soils of polar and nonpolar organic compounds at low relative concentrations (1998) *Environ. Sci. Technol.*, 32, pp. 338-343. , doi:10.1021/es970608g

- Cobelo-Garcia, A., Turner, A., Millward, G.E., Couceiro, F., Behaviour of palladium(II), platinum(IV), and rhodium(III) in artificial and natural waters: Influence of reactor surface and geochemistry on metal recovery (2007) *Anal. Chim. Acta*, 585, pp. 202-210
- Colton, J.B., Knapp, F.D., Burns, B.R., Plastic particles in surface waters of the Northwestern Atlantic (1974) *Science*, 185, pp. 491-497. , doi:10.1126/science.185.4150.491
- Coors, A., Jones, P.D., Giesy, J.P., Ratte, H.T., Removal of estrogenic activity from municipal waste land-fill leachate assessed with a bioassay based on reporter gene expression (2003) *Environ. Sci. Technol*, 37, pp. 3430-3434. , doi:10.1021/es0300158
- Deng, L., Liu, Y., Chen, P., Wang, L., Deng, N., Determination of trace bisphenol A in leachate by solid phase microextraction coupled with high performance liquid chromatography (2006) *Anal. Lett*, 39, pp. 395-404. , doi:10.1080/00032710500477183
- Derraik, J.G.B., The pollution of the marine environment by plastic debris: A review (2002) *Mar. Pollut. Bull*, 44, pp. 842-852. , doi:10.1016/S0025-326X(02)00220-5
- Desbrow, C., Routledge, E.J., Brighty, G.C., Sumpter, J.P., Waldock, M., Identification of estrogenic chemicals in STW effluent. 1. Chemical fractionation and in vitro biological screening (1998) *Environ. Sci. Technol*, 32, pp. 1549-1558. , doi:10.1021/es9707973
- Di Toro, D. M. et al. 1991 Technical basis for establishing sediment quality criteria for nonionic organic chemicals using equilibrium partitioning. *Environ. Toxicol. Chem.* 10, 1541-1583. (doi:10.1897/1552-8618 (1991) 10[1541:TBFESQ]2.0.CO
- 2)Earth Trends Country Profiles 2007 See <http://earthtrends.wri.org/country-profiles/index.php?theme=5Ejertsson>, J., Nilsson, M. L., Kylin, H., Bergman, A., Karlson, L., öquist, M. & Svensson, B. H. 1999 Anaerobic degradation of nonylphenol mono- and diethoxylates in digester sludge, landfill municipal solid waste and landfill sludge. *Environ. Sci. Technol.* 33, 301-306. (doi:10.1021/es980669u)Ejertsson, E., Karlsson, A., Lagerkvist, A., Hjertberg, T., Svensson, B.H., Effects of co-disposal of wastes containing organic pollutants with municipal solid waste - a landfill simulation study (2003) *Adv. Environ. Res*, 7, pp. 949-960. , doi:10.1016/S1093-0191(02)00099-0
- Endo, S., Takizawa, R., Okuda, K., Takada, H., Chiba, K., Kanehiro, H., Ogi, H., Date, T., Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: Variability among individual particles and regional differences (2005) *Mar. Pollut. Bull*, 50, pp. 1103-1114. , doi:10.1016/j.marpolbul.2005.04.030
- Erickson, M.D., (1997) *Analytical Chemistry of PCBs*, Boca Raton, CA: Lewis Publisher
- Eriksson, C., Burton, H., Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island (2003) *Ambio*, 32, pp. 380-384
- (2002) Use, exposure and loss data for the use of mono/di-tin compounds as PVC stabilizers, , ESPA, Communication from the European Stabilizers Producers Association
- (2003) Technical guide document on risk assessment, , European Chemicals Bureau, Institute for Health and Consumer Protection
- Foster, P.M.D., Disruption of reproductive development in male rat offspring following in utero exposure to phthalate esters (2006) *Int. J. Androl*, 29, pp. 140-147. , doi:10.1111/j.1365-2605.2005.00563.x
- Fromme, H., Kuchler, T., Otto, T., Pilz, K., Muller, J., Wenzel, A., Occurrence of phthalates and bisphenol A and F in the environment (2002) *Water Res*, 36, pp. 1429-1438. , doi:10.1016/S0043-1354(01)00367-0
- Fry, D.M., Fefer, S.I., Sileo, L., Ingestion of plastic by Laysan albatrosses and wedge-tailed shearwaters in the Hawaiian Islands (1987) *Mar. Pollut. Bull*, 18, pp. 339-343. , doi:10.1016/S0025-326X(87)80022-X
- Furtmann, K., (1996) *Phthalates in the aquatic environment*, p. 136. , Bruxelles, Belgium: ECPI
- Giam, C.S., Atlas, A., Powers, J.M.A., Leonard, J.E., Phthalic acid esters (1984) *Handbook of environmental chemistry*, 3, pp. 67-140. , ed. O. Hutzinger, pp, New York, NY: Springer Verlag

- Gilbert, J., Stain, J.R., McGuinness, J.D., Compositional analysis of commercial PVC bottles and studies of aspects of specific and overall migration into foods and stimulants (1986) *Food Addit. Contam.*, 3, pp. 133-144
- Gregory, M.R., Environmental implications of plastic debris in marine settings-entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions (2009) *Phil. Trans. R. Soc. B*, 364, pp. 2013-2025. , doi:10.1098/rstb.2008.0265
- Grun, F., Blumberg, B., Perturbed nuclear receptor signaling by environmental obesogens as emerging factors in the obesity crisis (2007) *Rev. Endocr. Metab. Disord.*, 8, pp. 161-171. , doi:10.1007/s11154-007-9049-x
- Hatzinger, P. B. & Alexander, M. 1997 Biodegradation of organic compounds sequestered in organic solids or in nanopores within silica crystals. *Environ. Toxicol. Chem.* 16, 2215-2221. (doi:10.1897/1551-5028 (1997) 0162.3.CO
- 2)Hu, J., Jin, F., Wan, Y., Yang, M., An, L., An, W., Tao, S., Trophodynamic behavior of 4-nonylphenol and nonylphenol polyethoxylate in a marine aquatic food web from Bohai Bay, North China: Comparison to DDTs (2005) *Environ. Sci. Technol.*, 39, pp. 4801-4807. , doi:10.1021/es048735h
- Huang, W.L., Webber, J.W., A distribution reactivity model for sorption by soils and sediments. 10. Relationships between desorption, hysteresis, and the chemical characteristics of organic domains (1997) *Environ. Sci. Technol.*, 131, pp. 2562-2569
- Huang, W.L., Yu, H., Weber, W.J., Hysteresis in sorption and desorption of hydrophobic organic contaminants by soils and sediments (1998) *Environ. Sci. Technol.*, 32, pp. 3549-3555. , doi:10.1021/es970764n
- Jonsson, S., Phthalates in landfill leachates - a signature of their degradation: Analytical aspects and toxicological considerations (Diss.) (2003) *Linköping Studies in Arts and Science*, (268). , Linköping University, Sweden
- Jonsson, S., Ejlertsson, J., Svensson, B.H., Behaviour of mono and diesters of o-phthalic acid in leachates released during digestion of municipal solid waste under landfill conditions (2003) *Adv. Environ. Res.*, 7, pp. 181-192
- Jonsson, S., Ejlertsson, J., Ledin, A., Mersiowsky, I., Svensson, B.H., Mono- and diesters from o-phthalic acid in leachates from different European landfills (2003) *Water Res.*, 37, pp. 609-617. , doi:10.1016/S0043-1354(02)00304-4
- Jonsson, S., Vavilin, V.A., Svensson, B.H., Phthalate hydrolysis under landfill conditions (2006) *Water Sci. Technol.*, 53, pp. 119-127
- Joo, J.C., Kim, J.Y., Nam, K., Mass transfer of organic compounds in dilute aqueous solutions in high density polyethylene geomembranes (2004) *J. Environ. Eng.*, 130, pp. 175-183
- Karapanagioti, H.K., Klontza, I., Testing phenanthrene distribution properties of virgin plastic pellets and plastic eroded pellets found on lesvos island beaches (Greece) (2008) *Mar. Environ. Res.*, 65, pp. 283-290
- Kawagoshi, Y., Fujita, Y., Kishi, I., Fukunaga, I., Estrogenic chemicals and estrogenic activity in leachate from municipal waste landfill determined by yeast twohybrid assay (2003) *J. Environ. Monit.*, 5, pp. 269-274. , doi:10.1039/b210962j
- Kawamura, Y., Koyama, Y., Takeda, Y., Yamada, T., Migration of bisphenol A from poly-carbonate products (1998) *J. Food Hyg. Soc. Jpn.*, 99, pp. 206-212
- Koch, H.M., Calafat, A.M., Human body burdens of chemicals used in plastic manufacture (2009) *Phil. Trans. R. Soc. B*, 364, pp. 2063-2078. , doi:10.1098/rstb.2008.0208
- Laist, D.W., Impacts of marine debris: Entanglement of marine life in debris including a comprehensive list of species with entanglement and ingestion records (1997) *Marine debris-sources, impacts and solutions*, pp. 99-140. , eds J. M. Coe & D. B. Rogers, pp, Berlin: Springer
- Maguire, R.J., Review on the persistence of nonylphenol and nonylphenol ethoxylates in aquatic environments (1999) *Water Qual. Res. J. Can.*, 34, pp. 37-78
- Mascarenhas, R., Santos, R., Zeppelini, D., Plastic ingestion by sea turtle in Paraiba, Brazil (2004) *Mar. Pollut. Bull.*, 49, pp. 354-355. , doi:10.1016/j.marpolbul.2004.05.006
- Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., Kaminuma, T., Plastic resin pellets as a transport medium for toxic

- chemicals in the marine environment (2001) *Environ. Sci. Technol*, 35, pp. 318-324. , doi:10.1021/es0010498
- Mato, Y., Takada, H., Zakaria, M.P., Kuriyama, Y., Kanehiro, H., Toxic chemicals contained in plastic resin pellets in the marine environment-spatial difference in pollutant concentrations and the effects of resin type (2002) *Kankyo Kagakukaishi*, 15, pp. 415-423
  - McDermid, K.J., McMullen, T.L., Quantitative analysis of small-plastic debris on beaches in the Hawaiian archipelago (2004) *Mar. Pollut. Bull*, 48, pp. 790-794. , doi:10.1016/j.marpolbul.2003.10.017
  - Meeker, J.D., Sathyanarayana, S., Swan, S.H., Phthalates and other additives in plastics: Human exposure and associated health outcomes (2009) *Phil. Trans. R. Soc. B*, 364, pp. 2097-2113. , doi:10.1098/rstb.2008. 0268
  - Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., A comparison of plastic and plankton in the North Pacific Central Gyre (2001) *Mar. Pollut. Bull*, 42, pp. 1297-1300. , doi:10.1016/S0025-326X(01)00114-X
  - Murata, T., The endocrine disruptors contained in the plastics (1999) *Chem. Eng*, 63, pp. 305-309
  - Murphy, S.R., Bertelo, R., Ringwood, M., Cochran, M., Improved organotin stabilizers: Continuing health and environmental research (2000) *J. Vinyl Addit. Technol*, 6, pp. 104-108. , doi:10.1002/vnl.10232
  - Nakada, N., Nyunoya, H., Nakamura, M., Hara, A., Iguchi, T., Takada, H., Identification of estrogenic compounds in wastewater effluent (2004) *Environ. Toxicol. Chem*, 23, pp. 2807-2815. , doi:10.1897/03-699.1
  - Nakada, N., Tanishima, T., Shinohara, H., Kiri, K., Takada, H., Pharmaceutical chemicals and endocrine disrupters in municipal wastewater in Tokyo and their removal during activated sludge treatment (2006) *Water Res*, 40, pp. 3297-3303. , doi:10.1016/j.watres.2006.06.039
  - Neal, R.A., Mechanisms of the biological effects of PCBs, polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans in experimental animals (1985) *Environ. Health Perspect*, 60, pp. 41-46. , doi:10.2307/3429943
  - Neidlinger, H.H., Schissel, P., *Polymers in solar technologies* (1987) *Polymers for advanced technologies*. IUPAC international symposium, , ed. W. Lewin, New York, NY: VCH
  - Ng, K.L., Obbard, J.P., Prevalence of microplastics in Singapore's coastal marine environment (2006) *Mar. Pollut. Bull*, 52, pp. 761-767. , doi:10.1016/j.marpolbul.2005.11.017
  - Oehlmann, J., A critical analysis of the biological impacts of plasticizers on wildlife (2009) *Phil. Trans. R. Soc. B*, 364, pp. 2047-2062. , doi:10.1098/rstb.2008.0242
  - Park, J.K., Sakti, J.P., Hoopes, J.A., Transport of organic compounds in thermoplastic geomembranes. I: Mathematical model (1996) *J. Environ. Eng*, 122, pp. 800-806
  - Pignatello, J.J., Xing, B., Mechanisms of slow sorption of organic chemicals to natural particles (1996) *Environ. Sci. Technol*, 30, pp. 1-11. , doi:10.1021/es940683g
  - Reddy, M.S., Basha, S., Adimurthy, S., Ramachandraiah, G., Description of the small plastic fragments in marine sediments along the Alang-Sosiya ship-breaking yard, India (2006) *Est. Coast. Shelf Sci*, 68, pp. 656-660. , doi:10.1016/j.ecss.2006.03.018
  - Reichenberg, F., Mayer, P., two complementary sides of bioavailability: Accessibility and chemical activity of organic contaminants in sediments and soils (2006) *Environ. Toxicol. Chem*, 25, pp. 1239-1245. , doi:10.1897/05-458R.1
  - Rios, L.M., Moore, C., Jones, P.R., Persistent organic pollutants carried by synthetic polymers in the ocean environment (2007) *Mar. Pollut. Bull*, 54, pp. 1230-1237. , doi:10.1016/j.marpolbul.2007.03.022
  - Robards, M.D., Piatt, J.F., Wohl, K.D., Increasing frequency of plastic particles ingested by seabirds in the subarctic North Pacific (1995) *Mar. Pollut. Bull*, 30, pp. 151-157. , doi:10.1016/0025-326X(94)00121-O
  - Rogers, C.E., Stanett, V., Szwarc, M., The sorption, diffusion, and permeation of organic vapors in polyethylene (1960) *J. Polym. Sci*, 45, pp. 61-82. , doi:10.1002/pol.1960.1204514506
  - Ryan, P.G., Connell, A.D., Gardener, B.D., Plastic ingestion and PCBs in seabirds: Is there a relationship? (1988) *Mar. Pollut.*

Bull, 19, pp. 174-176. , doi:10.1016/0025-326X(88)90674-1

- Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., Monitoring the abundance of plastic debris in the marine environment (2009) *Phil. Trans. R. Soc. B*, 364, pp. 1999-2012. , doi:10.1098/rstb.2008.0207
- Sakai, S., Urano, S., Takatsuki, H., Leaching behavior of PCBs and PCDDs/DFs from some waste materials (2000) *Waste Manag*, 20, pp. 241-247. , doi:10.1016/S0956-053X(99)00316-5
- Sangam, H.P., Rowe, K., Migration of dilute aqueous organic pollutants through HDPE geomembranes (2001) *Geotext. Geomembr*, 19, pp. 329-357. , doi:10.1016/S0266-1144(01)00013-9
- Schulte-Oehlmann, U., Tillmann, M., Casey, D., Duft, M., Markert, B., Oehlmann, J., Xeon-estrogenic effects of bisphenol A in prosobranchs (mollusca: Gaastropoda: Prosbranchia) (2001) *Z. Umweltchem. Okotox*, 13, pp. 319-333
- Sonnenschein, C., Soto, A.M., An updated review of environmental estrogen and androgen mimics and antagonists (1998) *J. Steriod Biochem. Mol. Biol*, 65, pp. 143-150. , doi:10.1016/S0960-0760(98)00027-2
- Staples, C.A., Peterson, D.R., Parkerton, T.F., Adams, W.J., The environmental fate of phthalates: A literature review (1997) *Chemosphere*, 35, pp. 667-749
- Sumpter, J.P., Johnson, A.C., Lessons from endocrine disruption and their application to other issues concerning trace organics in the aquatic environment (2005) *Environ. Sci. Technol*, 39, pp. 4321-4332. , doi:10.1021/es048504a
- Takeuchi, I., Miyoshi, N., Mizukawa, K., Takada, H., Ikemoto, T., Omori, K., Tsuchiya, K., Biomagnification profiles of polycyclic aromatic hydrocarbons, alkylphenols and polychlorinated biphenyls in Tokyo Bay elucidated by  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  isotope ratios as guides to trophic web structure (2009) *Mar. Pollut. Bull*, 58, pp. 663-671
- Teuten, E.L., Rowland, S.J., Galloway, T.S., Thompson, R.C., Potential for plastics to transport hydrophobic contaminants (2007) *Environ. Sci. Technol*, 41, pp. 7759-7764. , doi:10.1021/es071737s
- Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., Lost at sea: Where is all the plastic? (2004) *Science*, 304, p. 838. , doi:10.1126/science.1094559
- Thompson, R.C., Swan, S.H., Moore, C.J., vom Saal, F.S., Our plastic age (2009) *Phil. Trans R. Soc B*, 364, pp. 1973-1976. , doi:10.1098/rstb.2009.0054
- Thompson, R.C., Moore, C.J., vom Saal, F.S., Swan, S.H., Plastics, the environment and human health: Current consensus and future trends (2009) *Phil. Trans R. Soc B*, 364, pp. 2153-2166. , doi:10.1098/rstb.2009.0053
- Tobolsky, A.V., Mark, H.F., (1980) *Polymer science material*, ed. E. Robert, Huntington, New York, NY: Krieger Publishing Company
- Treloar, L.R.G., (1974) *Introduction to polymer science*, London and Winchester, UK: Wykeham Publications (London) Ltd
- Vavilin, V.A., Jonsson, S., Svensson, B.H., Kinetic analysis of the transformation of phthalate esters in a series of stoichiometric reactions in anaerobic wastes (2005) *Appl. Microbiol. Biotechnol*, 69, pp. 474-484. , doi:10.1007/s00253-005-0061-3
- Vlietstra, L.S., Parga, J.A., Long-term changes in the type, but not amount, of ingested plastic particles in short-tailed shearwaters in the southeastern Bering Sea (2002) *Mar. Pollut. Bull*, 44, pp. 945-955. , doi:10.1016/S0025-326X(02)00130-3
- Voparil, I.M., Mayer, L.A., Dissolution of polycyclic aromatic hydrocarbons into the lugworm's (*Arenicola marina*) digestive fluids (2000) *Environ. Sci. Technol*, 34, pp. 1221-1228. , doi:10.1021/es990885i
- Wagner, T., (2003) *Factors controlling hydrophobic organic contaminant sorption to and desorption from municipal solid waste*, Masters thesis, North Carolina State University
- Weber, W.J., McGinley, P.M., Katz, L.E., A distributed reactivity for sorption by soils sediments. 1. Conceptual basis and equilibrium assessments (1992) *Environ. Sci. Technol*, 26, pp. 1955-1962. , doi:10.1021/es00034a012
- West, C., (2007) *The photodegradation of diazepam and its human metabolites in water*, PhD thesis, University of Plymouth, Plymouth, UK



- Brominated diphenyl ethers. Environmental Health Criteria 162 (1994) Proceedings of the International Programme on Chemical Safety, , WHO/IPCS, Geneva, Switzerland: WHO/IPCS
- Wintgens, T., Gallenkemper, M., Melin, T., Occurrence and removal of endocrine disrupters in landfill leachate treatment plants (2003) *Water Sci. Technol*, 48, pp. 127-134
- Wu, B., Taylor, C.M., Knappe, D.R.U., Nanny, M.A., Barlaz, M.A., Factors controlling alkylbenzene sorption to municipal solid waste (2001) *Environ. Sci. Technol*, 35, pp. 4569-4576. , doi:10.1021/es010893a
- Wurl, O., Obbard, J.P., A review of pollutants in the sea-surface microlayer (SML): A unique habitat for marine organisms (2004) *Mar. Pollut. Bull*, 48, pp. 1016-1030. , doi:10.1016/j.marpolbul.2004.03.016
- Xing, B.S., Pignatello, J.J., Dual-mode sorption of low-polarity compounds in glassy poly(vinyl chloride) and soil organic matter (1997) *Environ. Sci. Technol*, 31, pp. 792-799. , doi:10.1021/es960481f
- Yamamoto, T., Yasuhara, A., Shiraishi, H., Nakasugi, O., Bisphenol A in hazardous waste landfill leachates (2001) *Chemosphere*, 42, pp. 415-418. , doi:10.1016/S0045-6535(00)00079-5
- Yamashita, R., Takada, H., Murakami, M., Fukuwaka, M., Watanuki, Y., Evaluation of noninvasive approach for monitoring PCB pollution of seabirds using preen gland oil (2007) *Environ. Sci. Technol*, 41, pp. 4901-4906. , doi:10.1021/es0701863
- Yasuhara, A., Determination of organic components in leachates from hazardous waste disposal sites in Japan by gas chromatography-mass spectrometry (1997) *J. Chromatogr. A*, 774, pp. 321-332. , doi:10.1016/S0021-9673(97)00078-2
- Ye, S., Andrady, A.L., Fouling of floating plastic debris under Biscayne Bay exposure conditions (1991) *Mar. Pollut. Bull*, 22, pp. 608-613. , doi:10.1016/0025-326X(91)90249-R
- Ying, G.-G., Kookana, R.S., Degradation of five selected endocrine-disrupting chemicals in seawater and marine sediment (2003) *Environ. Sci. Technol*, 37, pp. 1256-1260. , doi:10.1021/es0262232
- Zhang, C., Zeng, G., Yuan, L., Yu, J., Li, J., Huang, G., Xi, B., Liu, H., Aerobic degradation of bisphenol A by *Achromobacter xylosoxidans* strain B-16 isolated from compost leachate of municipal solid waste (2007) *Chemosphere*, 68, pp. 181-190. , doi:10.1016/j.chemosphere. 2006.12.012