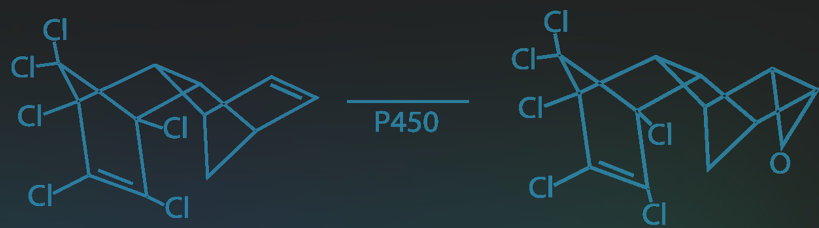
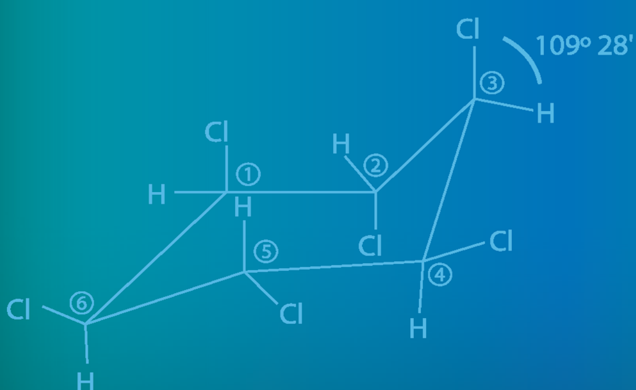
CRC Press
Taylor & Francis Group



The Toxicology and Biochemistry of Insecticides

SECOND EDITION



Simon J. Yu

The Toxicology and Biochemistry of Insecticides

SECOND EDITION

The Toxicology and Biochemistry of Insecticides

SECOND EDITION

Simon J. Yu

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper
Version Date: 20140930

International Standard Book Number-13: 978-1-4822-1060-6 (Hardback)

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Contents

Preface to the Second Edition

It has been six years since the first edition of this book was published. During this period, numerous new discoveries have been made in the field of insecticide toxicology, which justify inclusion in this book. Furthermore, many colleagues have used the first edition as a textbook for teaching insecticide toxicology. They have also given me some valuable suggestions to improve the book. In this new edition, I have retained the original format, but each chapter has been revised and updated, some quite extensively. In response to the reviewer's comments on the first edition, new references are added to each chapter for further reading. The following are some of the new features.

In Chapter 1, the introductory chapter, because of the potentially adverse effects of insecticides, some balance has been provided (i.e., the mention of human health hazards and environmental insults). In Chapter 2, the procedures for disposing pesticide containers are described. In Chapter 3, the new pollinator protective labeling for neonicotinoid insecticides is added. These label changes include a "Pollinator Protection Box" following the Environmental Hazards section as well as the new pollinator language in the Directions for Use section of each label.

In Chapter 4, several newly developed insecticides/acaricides (e.g., sulfoxaflor, cyenopyrafen, and cyflumetofen) are described, including their classification and biological activity. In addition, more microbial insecticides (bacteria, fungi, baculoviruses, and protozoa) are added in order to be in line with current integrated pest management (IPM) approaches. Various insect repellents, including synthetic chemicals and botanical products, are also presented.

In Chapter 7, the newly discovered modes of action of insecticides are described. For example, avermectin and fipronil act as blockers of glutamate-gated chloride channels. Pymetrozine exerts its repellent action by binding at nAChR sites. The diamide insecticides (chlorantraniliprole and cyantraniliprole) and ryanodine activate the ryanodine receptor, but they bind at different allosterically coupled sites. The mode of action of baculoviral insecticides and insect repellents are also described. Moreover, the known symptoms of insecticide poisoning in mammals are described.

In Chapter 8, the topic of metabolic pathways of insecticides has been expanded to include new classes of insecticides: formamidines, amidinohydrazones, phenylpyrazoles, thiadiazines, triazines, quinazolines, organotins, microbial insecticides, diacylhyrazines, nereistoxin analogs, thiocarbamates, organosulfurs, pyrazoles, diamides, tetronic acids, and dichloropropenyl ethers. This knowledge is important for assessing residual hazards to humans as well as studying mechanisms of insecticide resistance in insects. Furthermore, the structure of ATP-binding cassette transporter (also known as ABC transporter) and its role in xenobiotic metabolism are described.

In Chapter 9, the topic of insecticide selectivity has been expanded to include (1) the selectivity of pyrethroids, oxidizones, diamides, Bt, and diacylhydrazines, and (2) the toxicity of various insecticide classes on arthropod natural enemies of agricultural pests. The latter is an important consideration in IPM programs.

In Chapter 10, insecticide resistance has been updated and greatly expanded. These include (1) a discussion on the mechanisms of the reversion of insecticide resistance in the absence of insecticide pressure; (2) new mechanisms of insecticide resistance, such as mutations in the mitochondrial electron transport chain and chitin synthase, gene amplification of cytochrome P450 monooxygenases, chimeric P450s, and ABC transporter–mediated resistance; (3) the pattern of resistance development; and (4) fitness costs of insecticide resistance in insects. Due to the problem of insecticide resistance coupled with the slowdown in the development of new insecticides, insecticide resistance management has become more important as a means to preserve existing insecticides.

In Chapter 11, the topic of microbial degradation has been expanded to include (1) bioremediation of pesticide pollution in the environment and (2) symbiont-mediated insecticide tolerance. Also included are certain synthetic pyrethroid and organophosphorus insecticides, which have recently been found to possess hormone agonist and antagonist activities.

I hope this new edition will be useful to students of entomology, plant medicine, pest management, and other disciplines related to agriculture. I also hope that this book will be used as a textbook for teaching insecticide toxicology to graduate students.

I wish to thank my editor, John Sulzycki, and project coordinator, Jill Jurgensen, at CRC Press, Taylor & Francis Group, for their valuable assistance. Finally, I thank my wife, Rachel, for her continued support and patience during this revision.

Simon J. Yu

Preface to the First Edition

There is a scarcity of textbooks in insect toxicology and most of these books are rather outdated. I have written this book to address the need for a current text, and to provide the student of entomology, crop protection, plant medicine, and other disciplines related to agriculture with the general knowledge of insecticides. The book also brings together the most current knowledge on insecticide action and use. The 11 chapters in this book are concerned with insecticide formulation, classification, bioassay, mode of action, biotransformations in living organisms, resistance in insects, impact on the environment, and the laws that regulate their use. Since we are dealing with chemical compounds and their interaction with living organisms, my approach to most of these subjects is through chemical and biochemical principles. With the advent of molecular biology, numerous new findings have been reported in the areas of insecticide action and resistance mechanisms at the gene level. Although these subjects are not covered in much detail, the discussions are thorough enough for the serious reader to continue his or her study with more advanced literature.

Pesticides are an important component in pest management strategies for food production and public health. Despite their importance, these chemicals are often blamed for environmental pollution and nontarget toxicities. In fact, few other chemicals commonly used by our society are more closely scrutinized. Moreover, insects can develop resistance with frequent applications of pesticides. All of these issues have changed pest control from the simple task of the olden days into the complex, publicly sensitive operation of today. People who develop and supervise modern pest control methods must be highly trained in many areas of pesticide usage. Therefore, in order to use pesticides safely and effectively, not only must we know which pesticides to use in specific conditions, but we must also understand all biological, physiological, and environmental consequences.

I hope this book will provide students with sufficient background for the future use of pesticides and that it will prove valuable to all who are interested in pesticides.

The format of this book is based primarily on the late Professor L.C. Terriere's unpublished teaching material entitled "The Biochemistry and Toxicology of Insecticides" (1982). We talked about the possibility of coauthoring a new textbook in insecticide toxicology because of the clear need for such material. Unfortunately, he passed away before it could materialize. I dedicate this book to Professor Terriere in appreciation of his valuable contributions to insect toxicology and biochemistry, and the many years of research association.

I thank Drs. S.M. Valles, E. McCord, Jr., M.E. Scharf, L.T. Ou, and three anonymous reviewers for reviewing the manuscript and providing much helpful advice. I thank Susan Duser, Mike Sanford, and Sam Nguyen, who made many excellent computer drawings and figures. Thanks also to my editor, John Sulzycki, and project coordinator, Patricia Roberson, at Taylor & Francis Group, LLC, for their valuable assistance. Finally, I thank my wife, Rachel, for her mental support, and my sons, Robert and Edmund, for their help.

Simon J. Yu

Author

Simon J. Yu (Simon S.J. Yu), PhD, is professor emeritus at the University of Florida in Gainesville. He earned his BS in entomology from National Taiwan University, Taiwan, and an MS and a PhD in entomology from McGill University in Montreal, Canada, where he specialized in insect toxicology. After completing postdoctoral studies at Cornell University and Oregon State University, he served as assistant professor at Oregon State University from 1974 to 1979. He moved to the University of Florida in 1980. He was promoted to associate professor in 1982 and professor in 1986. He retired from the university in 2006, but remains an emeritus faculty. Dr. Yu's research interests include detoxification mechanisms, insecticide resistance, and enzyme induction in insects. His research has been supported by the USDA, NSF, NIH, EPA, and various pesticide companies. He has published more than one hundred scientific papers in various refereed journals and seven book chapters pertaining to insect toxicology. He has also published a textbook entitled *The Toxicology and Biochemistry of Insecticides*, 1st edition (2008) and 2nd edition (2014), CRC Press. He has presented over 50 papers at scientific meetings. He served as the major professor for MS and PhD students and supervisor for postdoctoral associates. He also taught a graduate course in insect toxicology in the Entomology/Nematology Department. Since his retirement, he continues to teach a course in insect toxicology, in distance education form, to off-campus graduate students.

CHAPTER 1

Need for Pesticides and Their Pattern of Use

1.1 INTRODUCTION

Pesticides are chemical substances used for controlling pests. The Environmental Protection Agency (EPA), which is the primary regulator of pesticides in the United States, defines a pesticide more precisely: A pesticide is any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pest. Pesticides include insecticides, nematicides, rodenticides, herbicides, and fungicides. They are the largest group of poisonous substances that are widely broadcast today. There are approximately 1,200 active ingredients approved for use by the EPA from which over 20,000 pesticides products are formulated and are being marketed in the United States.

The world population reached 7 billion in 2011 and is estimated to reach 8.04 billion by the year 2025. To properly feed and clothe these additional people, food crop yields need to be increased and more natural fibers produced. It is projected that global food demand will double in the next 50 years. Agricultural experts believe that these food and fiber needs can be met, but to do so will require the increased use of pesticides.

It should be mentioned that most pesticides, especially insecticides, are not highly selective. They are generally toxic to various nontarget species, including humans. Thus, we must use these chemicals carefully and scientifically in order to minimize their exposure to nontarget organisms.

Insecticide application is not always efficient. For example, it has been estimated that in an aerial spray of insecticide, 45% of the insecticide reaches an infested crop and less than 4% of the insecticide actually reaches the insect pest (Von Rumker et al., 1975). In this case, more than 50% of the insecticide reaches off-target crop; such insecticide is wasted and will pollute the environment. Therefore, the use of pesticides must take into consideration a balance between benefits of pest control and risks to human health and the environment.

1.2 NEED FOR PESTICIDES

1.2.1 Food Production

One of the major benefits of pesticides is the protection of crop yields. According to the National Research Council (2000), removing pesticides from U.S. agriculture would cause crop production to decline as much as 50%, depending on the crop species. Moreover, farm exports would decrease by 50%, and consumer expenditures for food would increase—and be accompanied by an increase in inflation—as food prices increase. It was concluded that chemical insecticides should remain part of a larger toolbox of diverse pest management tactics in the foreseeable future. More recently, Richard (2010) found that in the United Kingdom, without the application of pesticides to control insects, disease, and weeds, crop yields would fall to half their current levels and food prices would rise by 40%.

According to Ware and Whitacre (2004), about one-third of the world's food crops are destroyed by pests during growth, harvesting, and storage. Losses are even higher in developing countries. For example, in Latin America, approximately 40% of crops are lost due to pests. Cocoa production in Ghana has been tripled by the use of insecticides to control just one insect pest species. Sugar production in Pakistan was increased one-third due to the use of insecticides. The Food and Agriculture Organization has estimated that 50% of cotton production in developing countries would be destroyed without the use of insecticides. In the United States alone, crop losses due to pests are estimated to be 30% or $33 billion annually.

What would the losses be without pesticides? The need for controlling pests varies with the pest situations and with the crop. There are some crops that could not be produced if insects and diseases were not controlled. As shown in Table 1.1, wheat in the untreated sample was totally destroyed by wheat mites. There are some others that would survive but would produce poor quality, and there are still others where the control of pests provides only marginal benefits. There is no doubt that pesticides increase the profits of farmers by reducing the need for hand labor, increasing yields, assisting in the management of harvests, preventing losses in storage, and providing a more salable product (Terriere, 1982). It has been estimated that the farmer received approximately $4 in return for every dollar spent on pesticides (Pimentel et al., 1992).

A recent study shows that approximately 45 million acres of the United States (under 2% of the total acreage) are treated with insecticides each year to control insect pests. For some crops, losses

Table 1.1 Comparison of Losses Caused by Insects in Plots Treated by Conventional Use of Insecticides and Untreated Plots

	Calculated Losses (%)		
Commodity	With Treatment	Without Treatment	Increased Yield (%)
Corn			
Southwestern corn borer	9.9	34.3	24.4
Leafhopper on silage corn	38.3	76.6	38.4
Corn rootworm	5.0	15.7	10.7
Soybean			
Mexican bean beetle	0.4	26.0	25.6
Stink bugs	8.5	15.0	6.5
Velvet bean caterpillar	2.4	16.6	14.2
Looper caterpillar	10.5	25.5	15.0
Wheat			
Brown wheat mite	21.0	100.0	79.0
Cutworms	7.7	54.7	47.0
Wheat grubs	9.3	39.0	29.7
Cotton			
Boll weevil	19.0	30.9	11.9
Bollworm	12.1	90.8	78.7
Pink bollworm	10.0	25.5	15.5
Thrips	16.7	57.0	40.3
Potato			
Colorado potato beetle	1.0	46.6	45.6
European corn borer	1.5	54.3	52.8
Potato leafhopper	0.4	43.2	42.8

Source: From Ware, G.W. and Whitacre, D.M., *The Pesticide Book*, 6th edn, MeisterPro Information Resources, Willoughby, OH, 2004, p. 12. With permission.

would be higher than 40%. Many crops would not be economically feasible without the use of insecticides, which costs $1.2 billion annually (Mossler et al., 2009). According to the CropLife Foundation (2007), insecticides are a necessity in crop protection. In the United States, more than 144 billion pounds of crops would be lost annually without the insecticide protection.

1.2.2 World Health Status

As shown in Table 1.2, many diseases can be transmitted to humans by insects, ticks, or mites. It has been documented by the World Health Organization and in other reports that the use of synthetic insecticides can markedly reduce the risk of insect-borne diseases, especially in the case of malaria (Nauren, 2007). According to Ware and Whitacre (2004), in 1955, malaria infected more than 200 million persons throughout the world. The use of insecticides has reduced the annual death rate from this disease from 6 million in 1939 to 2.5 million in 1965 to about 1 million in 1991. Because of the use of insecticides, similar progress has been made in controlling other important tropical diseases including yellow fever, sleeping sickness, and Chagas' disease. Presently, we face the danger of contracting such diseases as encephalitis, typhus, relapsing fever, and sleeping sickness. Furthermore, in recent years, probably the increased movement of people (modern air transport) has brought a new insect-borne disease to North America. The West Nile virus (WNV), first reported in New York State in 1999, has spread over the Unites States. In 2002, there were 3900 human cases of WNV, which caused 247 deaths in the United States. The virus, believed to be spread by mosquitoes, also infests domestic livestock and many other wildlife species.

Table 1.2 Some of the Most Common Diseases Known to Be Transmitted to Humans by Insects, Ticks, or Mites

Disease	Vector
African sleeping sickness	Tsetse flies
Anthrax	Horse flies
Bubonic plague	A rat flea
Dengue fever	Two mosquitoes
Dysenteries	Several flies
Encephalitides	Several mosquitoes
Endemic typhus	Oriental rat flea
Epidemic typhus	Human louse
Filariasis	Several mosquitoes
Hemorrhagic fevers	Several mites and ticks
Lyme disease	*Ixodes* spp. ticks
Malaria	*Anopheles* mosquitoes
Onchocerciasis	Several black flies
Leishmaniasis	Sandflies
Q fever	Ticks
Relapsing fevers	Several ticks
Rocky Mountain spotted fever	Two ticks
St. Louis encephalitis	*Culex pipiens*
Trypanosomiasis	Several flies
West Nile virus	Several mosquitoes
Yellow fever	Several mosquitoes

Source: Adapted from Ware, G.W. and Whitacre, D.M., *The Pesticide Book*, 6th edn, MeisterPro Information Resources, Willoughby, OH, 2004. With permission.

Among the household insect pests, cockroaches are associated with the incidence of bronchial asthma, particularly, in children. Cockroach's body parts, cast skin, egg shells, and fecal material contain several major and minor allergens involved in triggering an asthma attack (Helm et al., 1996; Yu and Huang, 2000). A majority of urban residents with asthma are sensitive to cockroach allergens. The fact that the number of cockroaches seen in the infested housing is correlated with the degree of cockroach sensitivity suggests that cockroach control could reduce the incidence of asthma (National Research Council, 2000).

From this information, it is clear that efforts to control these diseases will continue and that pesticides will constitute a major part of such efforts.

1.3 PATTERN OF USE

Pesticides are widely used in the world and on most major crops, although the percentage of each crop treated throughout the world is low. As shown in Table 1.3, in the United States, pesticide amount used was 1.1 billion pounds in 2007, which accounted for 22% of the world estimate of 5.2 billion pounds of pesticide use, 25% of world herbicide amount used, 10% of world insecticide amount used, 14% of world fungicide amount used, and 26% of other pesticide amount used (Grube et al., 2011). In 2007, the agricultural market consumed 80% of the conventional pesticides (684 million pounds totally) sold in the United States (Table 1.4). Industry and government used 12%, while home and garden consumed only 8%. The industrial and commercial categories include applications of pesticides used by pest control operators, turf and sod producers, floral and shrub nurseries, railroads, highways, and industrial plant sites. Government use includes federal and state pest suppression and eradication programs and municipal and state health protection efforts involving the control of disease vectors such as mosquitoes, flies, cockroaches, and rodents. This table also shows that 11% of the pesticides are used as insecticides/miticides, 62% as herbicides/plant growth regulators, and 8% as fungicides. Herbicides remained the most widely used pesticides in the three market sectors: agriculture, industry/commercial/government, and home and garden.

Table 1.5 shows that in 1997, more insecticides were applied to control insects in cotton and corn than other crops. Insecticide use on potatoes, other vegetables, apples, and citrus remained roughly constant between 1980 and 1997 (National Research Council, 2000). From Table 1.6, it is seen that in 1998, we heavily used organophosphorus insecticides for controlling termites, livestock pests, and mosquitoes. Organophosphorus insecticides have been one of the most important classes of insecticides used for protecting crops, livestock, and human health over the past 60 years. In the United States,

Table 1.3 World and U.S. Amount of Pesticide Active Ingredient Used in 2007

	World Market		U.S. Market		
Pesticide Type	Million Pounds	%	Million Pounds	%	U.S. Percentage of World Market
Herbicides[a]	2096	40	531	47	25
Insecticides	892	17	93	8	10
Fungicides	518	10	70	6	14
Others[b]	1705	33	439	39	26
Total	5211	100	1133	100	22

Source: From Grube, A. et al., *Pesticide Industry Sales and Usage. 2006 and 2007 Market Estimates*, Biological and Economic Analysis Division, Office of Pesticide Programs, Office of Chemical Safety and Pollution Prevention, U.S. Environmental Protection Agency, Washington, DC, 2011. http://www.epa.gov/opp00001/pestsales.

[a] Includes plant growth regulators.

[b] Includes nematicides, fumigants, and other miscellaneous conventional pesticides, and other chemicals used as pesticides such as sulfur, petroleum oil, and sulfuric acid.

Table 1.4 Volume of Conventional U.S. Pesticide Active Ingredient Used by Class and Sector in 2007

	Million Pounds					
Sector	**Herbicides**[a]	**Insecticides**[b]	**Fungicides**	**Nematicides**[c]	**Other**[d]	**Total**
Agriculture	442	65	44	108	25	684
Industry/commercial/government	46	14	19	24	4	107
Home and garden	43	14	7	1	1	66
Total	531	93	70	133	30	857

Source: From Grube, A. et al., *Pesticide Industry Sales and Usage. 2006 and 2007 Market Estimates*, Biological and Economic Analysis Division, Office of Pesticide Programs, Office of Chemical Safety and Pollution Prevention, U.S. Environmental Protection Agency, Washington, DC, 2011. http://www.epa.gov/opp00001/pestsales.

[a] Includes plant growth regulators.
[b] Includes miticides.
[c] Includes fumigants.
[d] Includes rodenticides and other miscellaneous conventional pesticides.

Table 1.5 Acreage and Amounts of Insecticides Applied to Major U.S. Crops in 1997

Crop	Acres (×1000)	Pounds (×1000)	Pounds per Acre
Cotton	13,808	19,300	1.398
Corn	80,277	17,500	0.218
Potatoes	1,362	3,300	2.423
Wheat	70,989	1,200	0.017
Soybeans	70,850	800	0.011
Other vegetables	3,526	5,300	1.503
Citrus	1,150	5,500	4.783
Apples	453	3,300	7.285

Source: Padgitt, M.D. et al., *Production Practices for Major Crops in US Agriculture, 1990–97*, Statistical Bulletin No. 969, U.S. Department of Agriculture, Economic Research Service, U.S. Printing Office, Washington, DC, 2000.

Table 1.6 Organophosphorus Insecticide Usage in Nonagricultural Sites in 1998 in the United States

Category	Million Pounds
Termites	4
Livestock and pets	4
Mosquitoes	3
Residential and commercial indoor	3
Grain storage facilities	2
Turf and ornamental	1

Source: EPA, Staff Background Paper 5.1, Summary of Organophosphate Pesticide Usage, TRAC, May 27, 98. http://epa.gov/oppfead1/trac/sumry5-1.htm.

the top 10 organophosphorus insecticides used in 2007 were chlorpyrifos, malathion, acephate, naled, dicrotophos, phosmet, phorate, diazinon, dimethoate, and azinphos-methyl (Grube et al., 2011). However, as shown in Table 1.7, their use has declined gradually since 1980, 55% from 1997 to 2007, and 61% from 1990 to 2007. In terms of world market value, between 1997 and 2010, there was a marked decrease in organophosphates, methylcarbamates, and pyrethroids accompanied by a marked increase in neonicotinoids and nonneuroactive insecticides (Figure 1.1) (Casida and Durkin, 2013).

Table 1.7 Amount of Organophosphorus Insecticide Active Ingredients Used in the United States in All Market Sectors, 1990–2007 Estimates

	All Insecticides	Organophosphorus Insecticides	
Year	Million Pounds	Million Pounds	% of All Insecticides
1980	228	131	57
1985	161	114	71
1990	121	85	70
1991	114	82	72
1992	116	84	72
1993	115	79	69
1994	124	83	67
1995	125	80	64
1996	116	75	65
1997	112	73	65
1998	103	66	64
1999	126	91	72
2000	122	88	72
2001	105	73	70
2002	130	59	45
2003	115	46	40
2004	114	46	40
2005	104	40	39
2006	99	37	38
2007	93	33	35

Source: From Grube, A. et al., *Pesticide Industry Sales and Usage. 2006 and 2007 Market Estimates*, Biological and Economic Analysis Division, Office of Pesticide Programs, Office of Chemical Safety and Pollution Prevention, U.S. Environmental Protection Agency, Washington, DC, 2011. http://www.epa.gov/opp00001/pestsales.

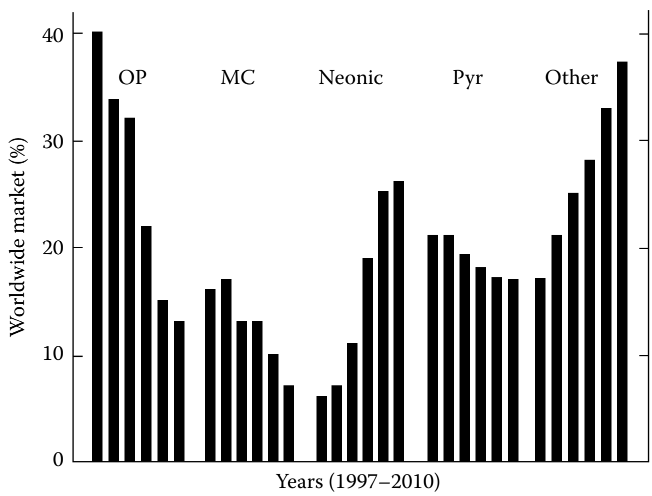


Figure 1.1 Changes in the use of insecticides between 1997 and 2010 for organophosphates (OPs), methylcarbamates (MCs), neonicotinoids (Neonic), pyrethroids (Pyr), and other compounds. In each class, the six bars represent data (from left to right) for 1997, 2000, 2002, 2005, 2008, and 2010. (Adapted from Casida, J.E. and Durkin, K.A., *Annu. Rev. Entomol.*, 58, 99, 2013.)

1.4 PESTICIDE ECONOMICS

Table 1.8 shows that in the United States, pesticide expenditures were about $12.5 billion, which accounted for 32% of the approximately $40 billion world market in 2007 (Grube et al., 2011). As shown in Figure 1.2, the four chemical classes of insecticides of major importance (organophosphates, carbamates, synthetic pyrethroids, and neonicotinoids) account for about 62% of the current global insecticide sales. Insect growth regulators such as juvenoids, ecdysone agonists (diacylhydrazines), and acylureas account for about 5% of the global market. The spinosyns, diamides, and sodium channel blockers (indoxacarb, metaflumizone) account for about 12% of the total market.

Pesticides have become increasingly expensive to develop. The present cost of discovery and development averages about $250 million per pesticide. On the average, a company must synthesize and screen 140,000 compounds for each one registered and sold commercially. Nowadays, the time period from discovery to initial sales ranges from 8 to 12 years (Sparks, 2013). Increased time and costs have had a significant impact on the rate of introduction of new pesticides and on their unit costs once they have been developed. One important reason for the slowdown in the development of new pesticides is that increasing restrictive legislation by the Congress and corresponding regulation by the EPA have increased both the costs and the time required for the process.

Table 1.8 World and U.S. Pesticide Expenditures at User Level by Pesticide Type, 2007 Estimates

	World Market		U.S. Market		
Pesticide Type	**Millions ($)**	**%**	**Millions ($)**	**%**	**U.S. Percentage of World Market**
Herbicides[a]	15,512	39	5,856	47	38
Insecticides	11,158	28	4,337	35	39
Fungicides	9,216	23	1,375	11	15
Others[b]	3,557	9	886	7	25
Total	39,443	100	12,454	100	32

Source: From Grube, A. et al., *Pesticide Industry Sales and Usage. 2006 and 2007 Market Estimates*, Biological and Economic Analysis Division, Office of Pesticide Programs, Office of Chemical Safety and Pollution Prevention, U.S. Environmental Protection Agency, Washington, DC, 2011. http://www.epa.gov/opp00001/pestsales.

[a] Includes plant growth regulators.

[b] Includes nematicides, fumigants, and other miscellaneous conventional pesticides, plus chemicals used as pesticides (e.g., sulfur and petroleum oil).

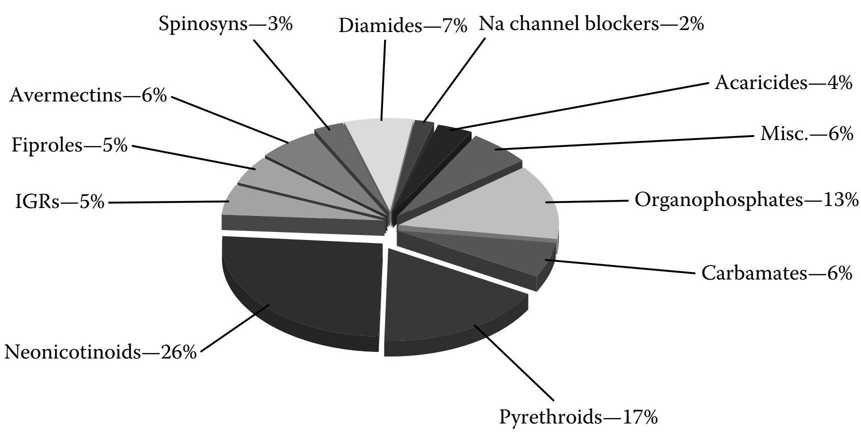


Figure 1.2 (See color insert.) Different chemical classes of insecticides and their global market share. (Adapted from Sparks, T.C., *Pestic. Biochem. Physiol.*, 107, 8, 2013.)

REFERENCES

Casida, J.E. and Durkin, K.A., Neuroactive insecticides: Targets, selectivity, resistance, and secondary effects, *Annu. Rev. Entomol.* 58, 99, 2013.

CropLife Foundation (n.d.), CPRI findings of new comprehensive study on insecticide use in United States. March 19, 2009. http://www.croplifefoundation.org, accessed April 20, 2009.

EPA (n.d.), Staff Background Paper 5.1, Summary of Organophosphate Pesticide Usage, TRAC 5/27/98. http://epa.gov/oppfead1/trac/sumry5-1.htm, accessed July 21, 2014.

Grube, A., Donaldson, D., Kiely, T., and Wu, L., *Pesticide Industry Sales and Usage. 2006 and 2007 Market Estimates*, Biological and Economic Analysis Division, Office of Pesticide Programs, Office of Chemical Safety and Pollution Prevention, U.S. Environmental Protection Agency, Washington, DC, 2011. http://www.epa.gov/opp00001/pestsales.

Helm, R., Cockrell, G., Stanley, J.S., Brenner, R.J., Burks, W., and Bannon, G.A., Isolation and characterization of a clone encoding a major allergen (*Bla g* Bd90K) involved in IgE-mediated cockroach hypersensitivity, *J. Allergy Clin. Immunol.* 98, 172, 1996.

Mossler, M., Fishel, F., and Whidden, N., Pesticide potpourri, *Chemically Speaking*, IFAS Extension, University of Florida, April 2009. http://pested.ifas.ufl.edu/newsletter.html.

National Research Council, *The Future Role of Pesticides in US Agriculture*, National Academy Press, Washington, DC, 2000.

Nauren, R., Insecticide resistance in disease vectors of public health importance, *Pest Manag. Sci.* 63, 628, 2007.

Padgitt, M.D., Newton, D., Penn, R., and Sandretto, C., *Production Practices for Major Crops in US Agriculture, 1990–97*, Statistical Bulletin No. 969, U.S. Department of Agriculture, Economic Research Service, U.S. Printing Office, Washington, DC, 2000.

Pimentel, D., Acquay, H., Biltonen, M., Rice, P., Silva, M., Nelson, J., Lipner, V., Giordano, S., Horowitz, A., and D'Amore, M., Environmental and economic costs of pesticide use, *Bioscience* 42, 750, 1992.

Richard, S., Food bill would rise $70 billion a year without pesticides, *Farmers Guardian*, p. 11, December 10, 2010.

Sparks, T.C., Insecticide discovery: An evaluation and analysis, *Pestic. Biochem. Physiol.* 107, 8, 2013.

Terriere, L.C., *The Biochemistry and Toxicology of Insecticides*, Oregon State University, Corvallis, OR, 1982.

Von Rumker, R., Kelso, G.K., Horay, F., and Lawrence, K.A., A study of the efficiency of the use of pesticides in agriculture, EPA 540/9-75-025, U.S. Environmental Protection Agency, Washington, DC, 1975.

Ware, G.W. and Whitacre, D.M., *The Pesticide Book*, 6th ed., MeisterPro Information Resources, Willoughby, OH, 2004.

Yu, S.J. and Huang, S.W., Purification and characterization of glutathione S-transferases from the German cockroach, *Blattella germanica* (L.), *Pestic. Biochem. Physiol.* 67, 36, 2000.

CHAPTER 2

Formulation of Pesticides

2.1 INTRODUCTION

With the exception of a few pesticides such as fumigants, pesticides are seldom used in their pure form. The technical-grade chemicals need to first be formulated as mixtures prior to application. Several thousand pesticides are registered for use by the Environmental Protection Agency (EPA) and sold in interstate commerce. Therefore, it is important to understand the principles involved in formulation since these influence the use and behavior of pesticides.

Pesticides are formulated by mixing active ingredients (AIs) with inert ingredients to make a combination that is effective and safe to use. In formulating a pesticide, important factors that need to be considered include the chemical and physical properties of the AI and the inert materials, the type of application equipment, the nature of the target surfaces, and the marketing and transport aspects of pesticide usage. We must know the properties of the toxicant, including melting point or boiling point, rate of hydrolysis, specific gravity, solubility, vapor pressure, ultraviolet degradation, and its inherent biological activity. We must also know the inert ingredient regarding its compatibility with AI, compatibility with container, and the physical properties of the ultimate mixture. Finally, the formulation itself must be evaluated to learn the homogeneity of the mixture, particle size, storage stability, retention by the target, wetting, penetration and translocation in plants, residual nature on a target or in the soil, nature of deposit, efficacy, and hazard to user (Terriere, 1982). The following references are useful for understanding pesticide formulations: Ware and Whitacre (2004), Anderson (1977), Hassall (1990), and Foy and Pritchard (1996).

2.2 TYPES OF FORMULATION

The following 12 formulations are commonly used in agriculture, in the home and garden, as well as those employed in structure and commercial pest control.

2.2.1 Dusts

Dusts usually contain two ingredients, an inert diluent and a toxicant. The latter accounts for only 1%–10% of the mixture. For this reason, dusts are more costly per pound of toxicant due to shipping costs. The inert ingredients of dusts must be relatively nonadsorptive to avoid inactivating the pesticides, for example, talc, pyrophyllite, or clay. They must be finely ground for ease of application and good coverage. Dusts have been the simplest formulations of pesticides to manufacture and easiest to apply. However, dusts are least effective and the least economical of the pesticide formulations because dusts tend to drift during application, resulting in a poor deposit to target surfaces. For instance, an aerial application of a standard dust formulation of pesticide will result in

10%–40% of the chemical reaching the crop (Ware and Whitacre, 2004). Another disadvantage is their inhalation hazard. From the standpoint of dermal toxicity to the user, however, dusts are usually safer than liquid formulation. A mixed blessing is the shorter residual life of pesticides applied as dusts compared to those as suspensions or emulsions.

Dusts are also formulated as dust concentrates to reduce shipping costs. These concentrates may contain 25%, 50%, or even 90% toxicant. They can be diluted with cheap local diluents by a simple process of mixing or blending prior to application. Currently, dusts are not much used, because of their drift potential and inhalation hazard and because of improvements in the other types of formulations.

2.2.2 Wettable Powders

A wettable powder (WP) is the most widely used agricultural formulation. It consists of a toxicant, inert diluents, and a wetting agent. The inert diluent is usually an adsorptive clay such as attapulgite. The wetting agent may be a blend of two or more surfactants. The toxicant usually comprises from 25% to 75% of the mixture. WPs are first prepared by spraying the toxicant (if liquid) onto the clay at a reasonable temperature. Another method is to mix the clay with a solution containing the toxicant (if solid) and then allowing the solvent to evaporate. WPs are sometimes prepared by the direct grinding of a crystalline toxicant along with a diluent. The objective in any case is to prepare a homogeneous mixture that can be ground to a fine powder.

As the name implies, WPs are designed to be mixed with water and applied as a spray. These are relatively safe on foliage (no phytotoxicity), but the spray mix requires constant mixing.

2.2.3 Emulsifiable Concentrates

This type of formulation is also designed to be applied as a spray by mixing with water to form an emulsion. The opaque emulsions are relatively stable requiring a minimum of agitation. An emulsifiable concentrate (EC) consists of a toxicant, a solvent for the toxicant, and an emulsifier (surfactant). Both solvent and surfactant may be a mixture of two or more substances. The toxicant content of ECs is expressed in terms of weight/volume rather than as weight/weight as with the WP. Thus, ECs may contain 2–4 pounds of toxicant per gallon, approximately equivalent to 25%–50% by weight.

ECs are usually more easily absorbed by the skin than WPs and dusts and are thus more hazardous if spilled on the applicator. Sensitive plants are more apt to be damaged by this formulation than by WPs since the solvent may increase penetration into the plant. On the other hand, the lack of masking by diluent probably increases the effectiveness of ECs over WPs (Terriere, 1982).

2.2.4 Suspendable Concentrates or Flowables

Some pesticides are so insoluble in the solvents used in ECs that they have to be formulated in other ways. In this case, these pesticides can be formulated to become water-based mixtures that can be handled and applied in the same manner as ECs. Basically, suspendable concentrate formulations that contain 50%–90% of a toxicant are WPs of small particle size (1–5 μm) that they remain in suspension for long periods. Suspendability and storage stability are improved by the inclusion of surfactants and various additives. Oils can be added when penetration of plants is desired.

2.2.5 Water-Soluble Powders

As the name implies, this group of insecticides used in water-soluble formulations easily dissolves in water. In this formulation, the technical-grade material is a finely ground solid. It can be added to the spray tank, where it dissolves quickly. Once dissolved, a soluble powder becomes an invisible solution that can be applied to approved surfaces without constant agitation. An example of such formulation is Orthene® PCO Pellets.

2.2.6 Solutions

A solution formulation is the true solution containing a toxicant and solvent, which can be used directly without further dilution. Solutions can be used for household insect sprays, roadside weed eradication, and rangeland spraying, whenever phytotoxicity is not a problem. In these cases, the toxicant can be dissolved in a low-cost solvent such as kerosene or fuel oil. Solutions do not contain surfactants because the solvent wets the target readily.

Some pesticides are sufficiently soluble in water to permit their formulation in water. However, this may not be done unless hydrolytic stability and toxicity hazard are favorable. Instead, such compounds are dissolved in a water-miscible solvent to avoid hydrolysis and then mixed with water prior to application.

2.2.7 Granules

A granular formulation is basically the same as a dust formulation. It contains a toxicant (1%–10%) and an inert diluent. The major difference is in the particle size; granules range from 20 to 100 mesh, while dusts pass through 300 mesh screens.

Granular particles can be prepared in several ways. The toxicant may be added so as to impregnate the granule and thus be completely released only when the granule breaks up. It may be surface coated on the granule using a volatile solvent, which evaporates from the formulation. The inert diluents can be clays or organic materials such as corncobs, pecan shells, tobacco stems, and walnut shells.

Granules are mostly used for application to soil and water. They are useful in a variety of insect control situations. Examples include application to the seedbed for seed protection, broadcasting and tilling into the soil for soil insect control, application to growing crops for either foliar or soil insect control, and application to ponds for mosquito control. They are easy to apply and are not as likely to drift as dusts or spray. They have less tendency to adhere to foliage and can thus be applied to soil surface through a canopy of leaves. Researchers often find that when different formulations of a toxicant are compared, the granules perform better.

2.2.8 Water-Dispersible Granules

A water-dispersible granule (WG) formulation contains typically a toxicant (50%–95%, w/w), dispersant, binder, and diluent. This formulation, also known as dry flowable, is intended for application after disintegration and dispersion in water by conventional spraying equipment. WGs are easier to use than WPs because they have low dust properties (due to larger particles) and exhibit good flowability.

2.2.9 Ultralow-Volume Formulations

Ultralow-volume (ULV) formulations are usually the undiluted technical-grade material or, in the case of solid, the original product dissolved in a minimum of solvent. They are applied without further dilution in an extremely fine spray generated by special aerial or ground spray equipment.

ULV formulations are useful for the control of public health, agricultural, and forest pests. ULV applications offer several advantages. The low volumes used—0.5 pt to 0.5 gal/acre, as compared with 3–10 gal/acre for normal spray—allow for either the use of simplified, light weight equipment or the very efficient use of equipment. This technique is useful in treating large areas. For example, an airplane carrying 100 gal of ULV malathion could spray 400–800 acres of rangeland before reloading. In orchard spraying, the spray tank may be as small as 5 gal instead of the commonly used 500 gal tank. Another advantage of ULV is the greater effectiveness of the toxicant, possibly because there are no inert ingredients or surfactants to mask the toxicant. This can result in reduced rate of application (Terriere, 1982).

2.2.10 Aerosols

Aerosols are commonly used for controlling resident flying and crawling insects such as mosquitoes and cockroaches. In principle, the AI is dissolved in a volatile petroleum solvent, and the resulting solution is atomized through a jet by means of a propellant. The propellant can be a gas under pressure or a liquid that is gaseous at atmospheric pressure. Chlorofluorocarbon used to be employed as a propellant, but has been replaced for environmental reasons with other volatile liquids, such as butane and dimethyl ether or by nonflammable compressed carbon dioxide or nitrogen (Ware and Whitacre, 2004).

2.2.11 Controlled-Release Formulations

Controlled-release (CR) formulations are a recent innovation in which the pesticide is incorporated into a carrier, generally a polymeric material (Scher, 1999). The rate of release of the pesticide is determined by the properties of the polymer itself as well as environmental factors. There are mainly two types of CR formulations: reservoir devices and monolithic devices. As shown in Figure 2.1, in the reservoir device, the toxicant is enclosed in capsules of thin polymeric material to become microcapsules (1–100 μm in diameter). In the monolithic device, the toxicant is uniformly dissolved or dispersed within the polymer matrix to become microparticles (1–100 μm in diameter) or strips. An example of this device is Hot Shot® No-Pest Strip in which dichlorvos is the AI. This type of formulations is used widely in pet flea and tick collars in which tetrachlorvinphos, tetrachlorvinphos/*S*-methoprene, propoxur, propoxur/*S*-methoprene, etc., are used as AIs currently.

Microcapsules are made by a two-step process mixing two chemical systems, the pesticide in a solvent and the capsule material, so that a wall forms around pesticide droplets (Figure 2.2). The size of the capsule can be controlled by mixing speed, by the chemical used, and by the conditions. The capsule material used will determine the nature of the wall, such as porosity and decomposition (Terriere, 1982).

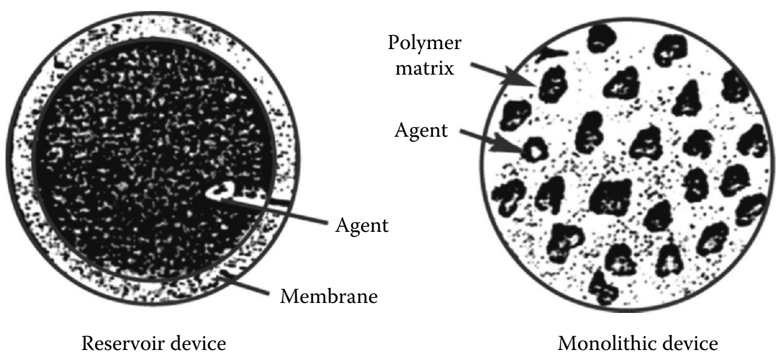


Figure 2.1 Reservoir and monolithic diffusion-controlled devices. (From Lewis, D.H. and Cowsar, D.R., Principles of controlled release pesticides, in: Scher, H.B. ed., *Controlled Release Pesticides*, ACS Symposium Series 53, American Chemical Society, Washington, DC, 1977, p. 1. With permission.)

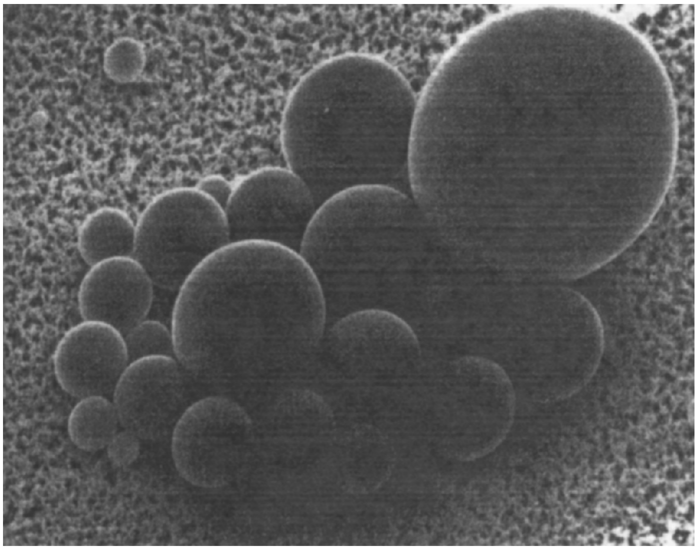


Figure 2.2 Electron micrograph of microcapsules on filter paper (1000×). (From Morgan, R.L. et al., Use of selected surfactants to reduce dermal toxicity of insecticides, in: Cross, B. and Scher, H.B. eds., *Pesticide Formulations: Innovations and Developments*, ACS Symposium Series 371, American Chemical Society, Washington, DC, 1988, p. 131. With permission.)

Three different mechanisms may be involved in controlling the release of biologically active compounds: (1) release through a membrane by diffusion; (2) removal of a protective wall by an enzyme, microorganisms, or chemical attack; and (3) release from chemical or physical bonds by temperature or moisture as shown in the following figure:

Synthesis

— — — — — — — — — — — ->

Polymer + pesticide Polymeric pesticide

<— — — — — — — — — — — -

Environment

These formulations can reduce worker exposure by decreasing pesticide toxicity and can minimize pesticide impact on the environment by reducing evaporation and leaching. Moreover, less insecticide is needed to achieve biological efficacy because of the reduction in environmental losses such as ultraviolet and soil degradation. There are also disadvantages, however, including expensive technology, longer lasting residues, and toxicity to bees (the microcapsules are approximately the same size as many pollen grains).

2.2.12 Baits

Baits can be very useful for achieving selective toxicity of insecticides against some species of insects. Spot application, that is, the placing of the bait in selected places accessible only to the target species, permits the use of insecticides in a safe manner with no environmental disruption. Several bait formulations are currently available on the market. For example, Amdro® Fire Ant Bait (containing hydramethylnon as toxicant) is an effective way to eliminate fire ants. Combat® Source Kill containing hydramethylnon or fipronil as toxicant controls cockroaches. Combat® Roach Killing Bait Strips contain fipronil as toxicant. Advion® Fire Ant Bait contains indoxacarb as toxicant. Harris Famous Roach Tablets, which contain boric acid as toxicant, are used for cockroach control. Raid® Ant Baits contain avermectin B_1 as toxicant. Hot Shot® Liquid Ant Bait contains dinotefuran as toxicant. In addition, a bait containing hexaflumuron or noviflumuron as toxicant is used in the Sentricon® Termite Elimination System and diflubenzuron as toxicant in the XTerra® Termite Bait System. Bait gels are common for household insect control. Examples are Maxforce Roach Bait Gel, which contains hydramethylnon or fipronil as toxicant, and Maxforce FC Professional Insect Control™ Ant Killer Bait Gel, which contains fipronil as toxicant. Advion® Cockroach Gel Bait contains indoxacarb as toxicant. GF-120 NF Naturalyte® Fruit Fly Bait is an insecticide bait for control of tropical fruit flies (Tephritidae). It contains a mixture of the insecticide spinosad, a microbially hydrolyzed protein, sugars, adjuvants, and a series of conditioners (Mangan et al., 2006).

A bait formulation consists of a carrier, toxicant, and feeding stimulants (phagostimulants). Carriers include laying mash, cracked corn, wheat bran, corncob grits, peanut hulls, and cottonseed meal. Feeding stimulants include crude cottonseed oil, refined soybean oil, sucrose, coax, brewer's concentrate (brewery by-product), malt extract, glucose, maltose, honey, and wheat germ oil. A malathion 4% bait formulated from crude cottonseed oil (5%) and sucrose (10%) on a laying mash carrier was very effective in controlling mole crickets in the field (Kepner and Yu, 1987). A microencapsulated bait called Slam®, which consists of cucurbitacins and 8% carbaryl, is also available for controlling corn rootworm adults. Cucurbitacins that are found in all cucurbits are feeding stimulants for corn rootworms.

It is important to know the concentration of insecticide on the label. For dry formulations such as WPs, dusts, and granules, the insecticide concentration is expressed in the percentage of AI in the formulation. For example, Diazinon® 50W means that 50% of diazinon is in the WP formulation. On the other hand, for liquid formulations such as solutions and ECs, the concentration of insecticide is expressed in pounds of AI/gal of the formulation. For example, Diazinon® 4E means that 4 lb of diazinon is in each gallon of the formulation.

2.3 NONPESTICIDAL INGREDIENTS OF FORMULATIONS

2.3.1 Solvents

Solvents are important ingredients of ECs and of solution formulations. When the formulation is to be used on crops, it is critical that a solvent be nonphytotoxic. The solvent must have a high level of solvent power if an EC is being formulated. Because most toxicants are insoluble in water, the solvent must also be water insoluble. Otherwise, when the EC is added to water in the spray tank, the solvent will mix with the water and leave the toxicant behind as a crystalline precipitate. The *carrying power* of the solvent, that is, the amount of pesticide it will hold in solution, is important in the storage stability of formulations. If near its saturation point at ordinary temperatures, it may exceed this at low temperatures with the result that solvent and pesticide may separate, causing crystal formation and phase separation (Terriere, 1982).

Heavy solvents (high specific gravity) are undesirable in most cases because it is hard to stabilize the emulsion when the EC is mixed with water. If the specific gravity of the solvent is near that of water, the setting tendency of the emulsion is decreased. The terms *top creaming* and *bottom creaming* are used to describe emulsions in which the insecticide-containing solvent has risen to the top or settled to the bottom of the emulsion. Other considerations in the choice of solvents for pesticide formulations include flammability, purity, odor, color, skin irritability (in animal dips and sprays), and cost (Terriere, 1982).

2.3.2 Diluents

Diluents, sometimes known as inerts or carriers, play an important role in the behavior of the formulated product. Diluents have been prepared from agricultural wastes such as walnut shells, pecan shells, tobacco stems, and corncobs; from minerals such as kaolinite, attapulgite, and talc; and from fossilized deposits such as diatom beds. The exact diluent used in a given preparation depends on cost, properties, and availability. Dusts require low sorptive inerts to minimize the toxicant–diluent interaction. For WPs, inerts must be high in sorptive power because they carry a large amount of toxicant especially when the toxicant is a liquid. Otherwise, the formulated product would be likely to cake badly in storage. It is required that a diluent must be truly inert. However, formulators often find that an inert diluent contains *hot spots* or alkalinity to inactivate part of the toxicant. In this case, urea can be used as a deactivator to counteract the undesirable effects in some dust and wettable formulations (Terriere, 1982).

2.3.3 Surfactants

Surfactants, also known as surface-active agents, are chemicals that will orient at an interface. They serve as coupling agents, joining two phases, liquid–liquid, liquid–solid, or liquid–air. When the phases being coupled are liquid–air, the surfactant may cause foaming and will be called a foaming agent. If the interfaces are liquid–solid, the surfactant may result in the wetting of the solid and will be called a wetting agent. In liquid–liquid interfaces, such as oils and water, the surfactant would be an emulsifier (emulsifying agent) because it allows oils and water to mix as an emulsion. There are more than 3000 commercial surfactants. They are grouped according to the type of action as follows: wetting agents, stabilizing agents (emulsifiers, dispersants), spreaders, penetrants, cosolvents (coupling agents), hygroscopic agents, or stickers (deposit builders) (Terriere, 1982).

Surfactants are divided into three main groups, based on their ionization in water; these are anionic surfactants, cationic surfactants, and nonionic surfactants. If on ionization one end of the molecule becomes a negative ion, the surfactant is known as an anionic surfactant as shown in Figure 2.3.

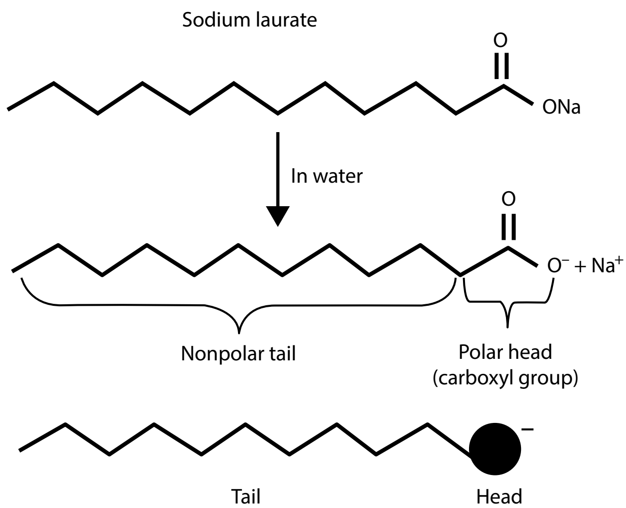


Figure 2.3 Ionization of sodium laurate in water.

Conversely, when a positive ion is formed, it is called a cationic surfactant. The following examples illustrate the structure and the ionization of surfactants:

1. Anionic surfactants:
   Sodium lauryl sulfate [$CH_3(CH_2)_{11}OSO_2O^- + Na^+$]
2. Cationic surfactants (quaternary ammonium compounds):
   Lauryl trimethylammonium chloride [$CH_3(CH_2)_{11}N(CH_3)_3^+ + Cl^-$]
3. Nonionic surfactants (polyethylene oxide derivatives):
   Triton X-100 [4-$(C_8H_{17})C_6H_4(OCH_2CH_2)_nOH$] (n = 9–10)

It can be seen that in each of the three types of surfactants, there is a chemical grouping that would be considered nonpolar in nature. This is usually a long-chain fatty acid (saturated hydrocarbon). The polar end of the molecule may be the sodium salt of an acid, the chloride salt of a quaternary nitrogen, or the free hydroxy group of a glycol ether.

As mentioned in the preceding text, when an anionic surfactant dissolves in water, it will ionize and disperse readily in water to form a micelle in which the negatively charged carboxylate groups orient in the water phase and form hydrogen bonds with water molecules, and the nonpolar insoluble hydrocarbon chains, which do not hydrogen-bond with water, are hidden within (Figure 2.4). On adding oil drops (from ECs) or solid particles (from WPs) in water, these particles will go to the center of micelles (Figures 2.5 and 2.6). Anionic surfactant micelles have a net negative charge and

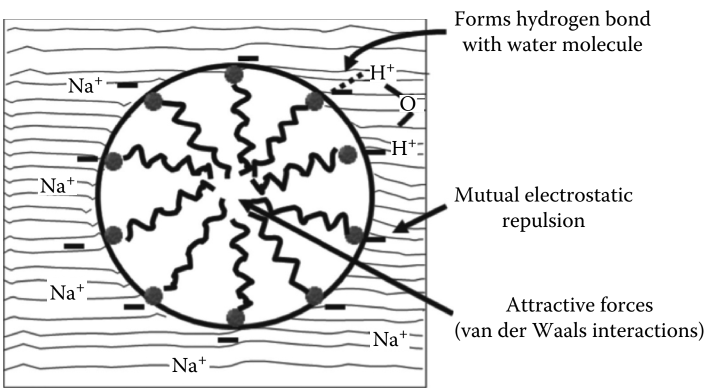


Figure 2.4 Sodium laurate micelle.

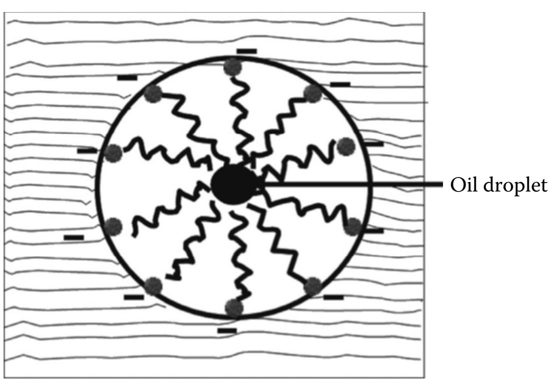


Figure 2.5 A micelle with an oil drop.

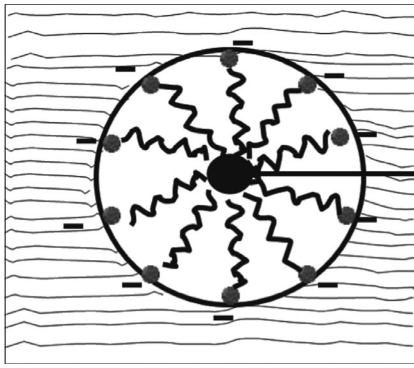


Figure 2.6 A micelle with a solid particle.

remain suspended because of mutual electrostatic repulsion. Cationic surfactants act in a similar manner as anionic surfactants except that the suspended particles are surrounded by a sphere of positive charges. In the case of nonionic surfactants, hydrophilic groups orient in the water phase and lipophilic groups orient in the oil or solid phase.

Ionic surfactants may cause complications with water during application. For example, in hard water, there is an excess of Ca^{2+}, Mg^{2+}, Fe^{2+}, SO_4^{--}, and other inorganic ions. These will react with the anionic or cationic ions of the surfactant to form insoluble salts, which precipitate, removing the surfactant from the spray solution. This will result in reducing the surface-active properties of the surfactant. For this reason, pesticide formulators often use both ionic and nonionic surfactants in their formulations. Because the latter agents do not ionize, they are not as likely to react with the constituents of hard water.

As we know, the surface tension of water is high. When droplets of water fall on waxy surfaces, they tend to form small spheres. If a surfactant is added to water, surfactant molecules will displace some water molecules from the surface, which lower the surface tension (Figure 2.7). As a result, the droplets can spread over the waxy surface and lose their spherical shape. Therefore, in addition to acting as surface-active agents in spray solutions, surfactants also lower the surface tension of water, thus increasing the area of contact.

Work is underway to use nanotechnology to develop new pesticide formulations called nanopesticides (e.g., nano emulsions and nanocapsules), which will increase the efficacy and reduce the environmental impact of pesticides (Kah and Hofmann, 2014).

2.4 DISPOSAL OF PESTICIDE CONTAINERS

Pesticides are toxic chemicals. Improper disposal of pesticides or their containers leads to environmental contamination and may face both civil and criminal penalties. The following procedures are appropriate for disposing of pesticide containers (Nesheim and Fishel, 2011).

Empty drums, bottles, or cans must be triple-rinsed before disposing of them as follows:

1. Empty all pesticide into the spray tank.
2. Fill the container about one-fourth full with water and rinse thoroughly.
3. Add the rinsate from the container to spray tank and drain the container in a vertical position for 30 s.
4. Repeat rinsing two more times.
   (Triple rinsing also can be replaced with pressure rinsing. This is done using a special pressure rinsing device that is inserted into the container for rinsing the inside of the container.)

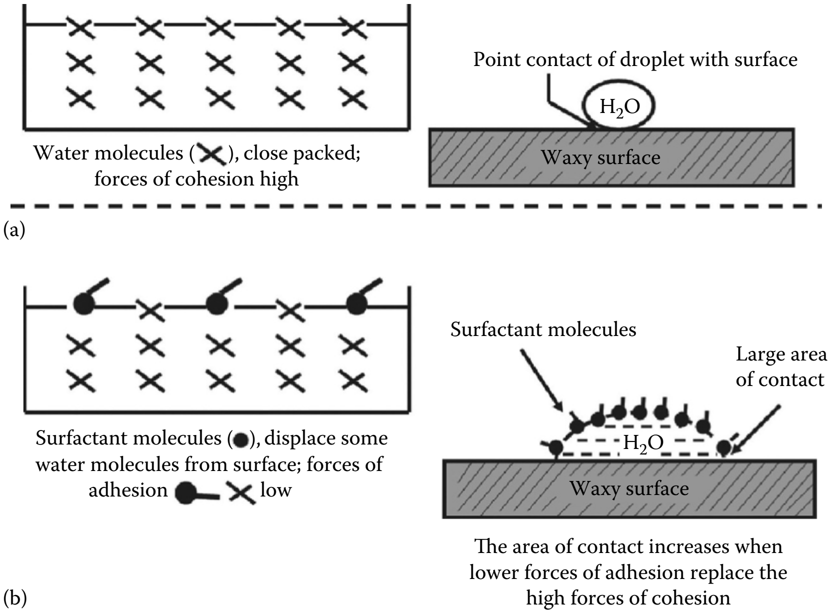


Figure 2.7 Effect of surfactant on surface tension. (a) Because of high forces of cohesion, there is little contact between droplet and surface in the absence of surfactants. (b) The area of contact increases when lower forces of adhesion replace the high forces of cohesion. (From Hassall, K.A., *The Biochemistry and Uses of Pesticides,* 2nd edn, VCH Publishers, Inc., New York, 1990, p. 55. With permission.)

5. Puncture the top and bottom of the container to prevent its reuse.
6. Dispose of the empty container in a sanitary landfill.
   Empty bags (dry formulations) should be shaken clean, opened both ends of the container to prevent its reuse, and then disposed of in a sanitary landfill.

2.5 PESTICIDE APPLICATION EQUIPMENT

Many types of equipment are available for applying pesticides. These include hand-operated sprayers, motorized sprayers, boomless sprayers, boom sprayers, airblast sprayers, granular applicators, and aerial applicators (fixed-wing aircraft or helicopters). Good results can be obtained when suitable equipment is selected for application. When selecting equipment, one needs to consider several factors including the size and type of area to be treated, the type of pest, the pesticide formulation, the required application accuracy, and cost of the equipment. Because of the scope of this book, readers interested in pesticide application equipment are referred to the following publications: Matthews (2000) and the website http://www.agf.gov.bc.ca/pesticides/f_2.htm.

REFERENCES

Anderson, W.P., *Weed Science: Principles*, West Publishing Co., St. Paul, MN, 1977, Chap. 7.

Foy, C.L. and Pritchard, D.W., *Pesticide Formulation and Adjuvant Technology*, Foy, C.L. and Pritchard, D.W., Eds., CRC Press, Boca Raton, FL, 1996.

Hassall, K.A., *The Biochemistry and Uses of Pesticides*, 2nd ed., VCH Publishers, New York, 1990.

Kah, M. and Hofmann, T., Nanopesticide research: Current trends and future priorities, *Environ Int*. 63, 224, 2014.

Kepner, R.L. and Yu, S.J., Development of a toxic bait for control of mole crickets (Orthoptera: Gryllotalpidae), *J. Econ. Entomol.* 80, 659, 1987.

Lewis, D.H. and Cowsar, D.R., Principles of controlled release pesticides, in *Controlled Release Pesticides*, Scher, H.B. Ed., ACS Symposium Series 53, American Chemical Society, Washington, DC, 1977, p. 1.

Mangan, R.L., Moreno, D.S., and Thompson G.D., Bait dilution, spinosad concentration, and efficacy of GF-120 based fruit fly sprays, *Crop Protect.* 25, 125, 2006.

Matthews, G.A., *Pesticide Application Methods*, 3rd edn., Blackwell Science, Inc., Oxford, U.K., 2000.

Morgan, R.L., Rodson, M., and Scher, H.R., Use of selected surfactants to reduce dermal toxicity of insecticides, in *Pesticide Formulations: Innovations and Developments*, Cross, B. and Scher, H.B., Eds., ACS Symposium Series 371, American Chemical Society, Washington, DC, 1988, p. 131.

Nesheim, O.N. and Fishel, F.M., Proper disposal of pesticide waste, University of Florida IFAS Extension, Publication #P1-18, 2011.

Scher, H.B., *Controlled Release Delivery System for Pesticides*, Scher, H.B. Ed., Marcel Dekker, New York, 1999.

Terriere, L.C., *The Biochemistry and Toxicology of Insecticides*, Oregon State University, Corvallis, OR, 1982.

Ware, G.W. and Whitacre, D.W., *The Pesticide Book*, 6th edn., MeisterPro Information Resources, Willoughby, OH, 2004.