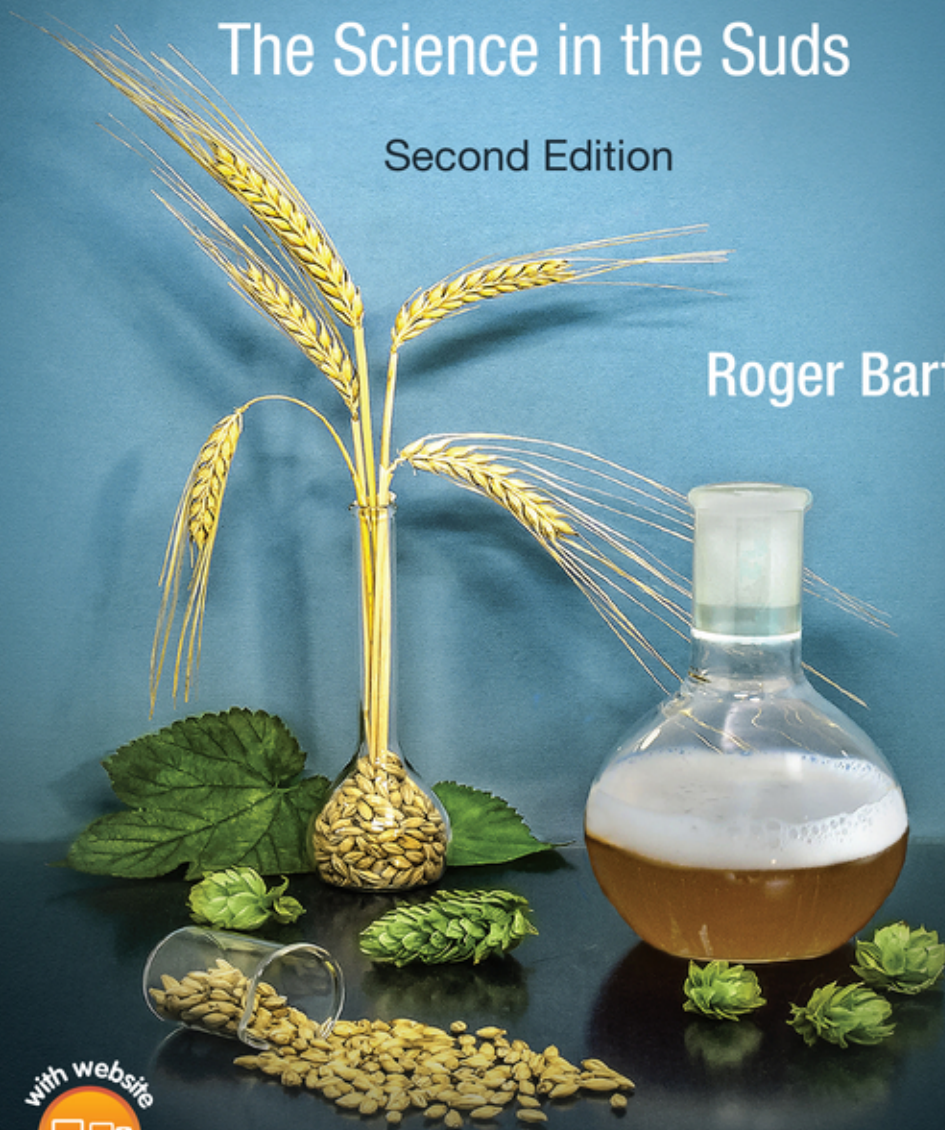


The Chemistry of **BEEER**

The Science in the Suds

Second Edition

Roger Barth



with website



WILEY

THE CHEMISTRY OF BEER

The Science in the Suds

THE CHEMISTRY OF BEER

The Science in the Suds

Second Edition

ROGER BARTH, PhD

WILEY

This edition first published 2022
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John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

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9600 Garsington Road, Oxford, OX4 2DQ, UK

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Library of Congress Cataloging-in-Publication Data

Names: Barth, Roger, author.

Title: The chemistry of beer : the science in the suds / Roger Barth, PhD.

Description: Second edition., | Hoboken, NJ : Wiley, [2022] | Previously published: 2013. | Includes bibliographical references and index.

Identifiers: LCCN 2022015130 (print) | LCCN 2022015131 (ebook) | ISBN 9781119783336 (paperback) | ISBN 9781119783343 (adobe pdf) | ISBN 9781119783350 (epub)

Subjects: LCSH: Beer. | Beer--Analysis.

Classification: LCC TP577 .B35 2022 (print) | LCC TP577 (ebook) | DDC 663/.42--dc23/eng/20220520

LC record available at <https://lccn.loc.gov/2022015130>

LC ebook record available at <https://lccn.loc.gov/2022015131>

Cover Design and Illustration: Marcy Barth

Cover Photograph: © Naomi Hampson

Set in 10/12pt TimesTenLTStd by Straive, Chennai, India

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PREFACE TO THE SECOND EDITION

Whether you are a serious brewer or a person who is just interested in beer, the more you know about the scientific basis of beer, its preparation, and its flavors, the more you will appreciate and enjoy the depth and diversity of the world of beer. Although this book is written largely for the general reader, there is material that will be useful to brewers or people who are considering taking up brewing as homebrewers or as professionals.

Commercial brewing and homebrewing are discussed to help give context to the material, but this is not intended to be a complete textbook on brewing, several of which, including *Mastering Brewing Science* by biologist Dr. Matthew Farber and me, are mentioned in the chapter sources. Nonetheless, it will be very helpful to read this book before reading one of the brewing textbooks.

Much has happened since the first edition of *The Chemistry of Beer: The Science in the Suds* was published in 2013. The craft brewing industry was hit hard by the Covid-19 pandemic at a time of increased competition and increasing demand for new products. Generational changes in the drinking public have brought several previously marginal products into the mainstream. These include low and no-alcohol beer, flavored malt beverages, and hard seltzer. Many brewers have responded by adding some of these products to their line-up. The preparation of these and other beer-related products are discussed in a new chapter.

Other changes were introduced to make the book clearer and more appealing to readers, and to respond to helpful suggestions. These include full color throughout, expanded coverage of beer history, with particular attention to the role of beer in development of technology and the contributions of the brewing industry to science and technology. The chapters on packaging and beer stability and those on flavor and beer styles have been combined to highlight the chemistry. The chapter on homebrewing now includes a section on careers in brewing. The recipes have been removed, but many recipes are available in books referenced in the Sources and on the Web. Each chapter now begins with a brief overview and ends with chapter highlights.

Many readers will be college students, some of whom are in the process of developing attitudes and practices regarding the use of alcohol. Alcohol is what it is. It has enriched many lives and ruined many lives, making it much like every other aspect of the human experience. It should not be taken lightly. I hope this book will help its readers attain a thoughtful approach to alcohol. Those who are experiencing difficulties with alcohol or other psychoactive substances should seek assistance from college, pastoral, or health counselors.

ROGER BARTH, PH.D.

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READING NOTES

Several typographic conventions are used throughout this book to signal the level of the material or the availability of additional information.

The first mention of a word that is defined in the glossary is in **boldface** type.

Supplementary material that may be glossed over or skipped altogether, as the requirements of the reader dictate, are highlighted in shaded boxes.

Questions marked with a bullet (■) are advanced and may depend on supplementary material (in shaded boxes).

These conventions are intended to help you to focus on the main points, while keeping the book useful for those with a need or desire to know more.

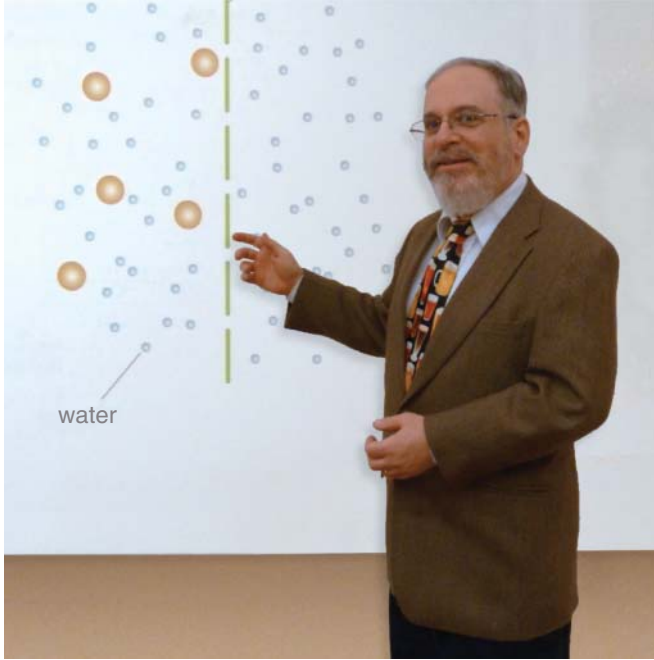
Each chapter has references to some of the key primary and secondary literature. Each chapter has a set of questions intended to help you study the material. There is an extensive glossary and a full index to help you navigate the book.

Thank you for reading!

ACKNOWLEDGMENTS

The second edition of *The Chemistry of Beer: The Science in the Suds* is built on the first edition. Both editions were built on support and assistance from many friends and colleagues who greatly enhanced the quality of this book. I deeply appreciate their irreplaceable contributions. Donna Marie Zoccoli, David Barth, and Tom Simpson read the ever-changing copy, corrected errors, and provided cogent editorial suggestions. Marcy Barth and Naomi Hampson did most of the photography, including on-site and studio photos. All unattributed photographs are the work of Marcy. Zach Miller was kind enough to conduct me and my daughter, Naomi Hampson, through the non-public parts of the new Victory Brewing Company facility in Parkesburg, Pennsylvania, allowing Naomi to photograph the state-of-the-art equipment. The West Chester University library gave outstanding service in locating and delivering books and journal articles, despite pandemic restrictions. Guy Hagner showed us around the splendid Susquehanna Brewing Company facility in Pittston, Pennsylvania when it was new. Joel Sprick gave us photo opportunities at Levante Brewing Company in West Chester, Pennsylvania. This small and very creative brewery gave me samples of outstanding fruit beers made with Philly Sour[®], the self-souring *Lachancea* yeast mentioned in Chapter 11.

Special acknowledgment goes to Marcy Barth, my wife of 37 years. The visual appeal of this book is due to her artistry and skilled work. In addition to camera work, she enhanced photos, staged studio scenes, and created artwork for many of the illustrations. She provided many sound editorial suggestions that greatly improved the book. Her constant support made this project possible.



Source: Roger Barth.

ABOUT THE AUTHOR

Roger Barth was born in New York City. He attended public schools in Levittown, Pennsylvania and received his bachelor's degree from La Salle College in Philadelphia. He was awarded a doctorate in Physical Chemistry at the Johns Hopkins University in Baltimore. After working on development of car catalysts at UOP Inc. in Des Plaines, Illinois, he did postdoctoral work on surface and catalytic chemistry at University of Delaware and at Drexel University. He taught chemistry at West Chester University of Pennsylvania from 1985 until his retirement in 2021. He developed a course entitled The Chemistry of Beer, and he wrote this book to serve as its textbook. He is the author of scientific articles about beer brewing and brewing safety. He is the coauthor, with Dr. Matthew Farber, of *Mastering Brewing Science: Quality and Production*, a comprehensive textbook for brewing science degree and certificate programs.

Dr. Barth is an accomplished home brewer. He and his wife, Marcy, a graphic designer, and their two cats live in West Goshen, Pennsylvania. They have three grown children and three grandchildren.

ABOUT THE COMPANION WEBSITE

This book is accompanied by a companion website:

<https://www.wiley.com/go/Barth/beer>

The website includes:

- Answers



CHAPTER 1

INTRODUCTION

CHAPTER 1 OVERVIEW

The story of beer is the story of the rise of civilization. To the stone-age brewers, making beer must have seemed like magic. The transformation of grain and water to beer is as impressive now as it was then. Today, we can understand the magic of beer through the science of chemistry. From purifying the water to packaging the beer, every brewing step has a scientific background. Science and technology owe more to beer than beer owes to science. Beer brewing led to many fundamental discoveries from the isolation of the first enzyme to the first explanation of a biochemical pathway. Brewing served as the application that drove inventions like pasteurization and mechanical refrigeration. Understanding the chemistry of beer will lead you toward a greater appreciation of the real magic of beer.

1.1 BRIEF HISTORY

Beer Origins

It is likely that our earliest ancestors were using **psychoactive** materials from the dawn of the human species. Based on practices of traditional cultures, we can guess that the experience could have connected the user, a **shaman**, to the spirit world. The shaman could then divine the future, heal diseases and injuries, and issue blessings or curses.

We may never know the full story of the first encounter of humans or their **hominid** predecessors with **ethanol**, the **alcohol** in **intoxicating** beverages. Perhaps it happened like this. A band of hunter-gatherers finds a rich field of berries and packs as many as they can into bags or baskets. In some containers, the berries at the bottom get crushed. When the group has eaten its way to the liquid, they find a unique but not unpleasant **aroma**. A short time later they notice the characteristic effects of ethanol, known in our day as **drunkenness**. The incident makes a big impression on them. After this, whenever they find sweet fruit, they put it in a container for a few days. Most of the time this process yields a drinkable alcoholic beverage. There are two major factors that made this early **wine**-making experiment successful. One factor is that fruit has simple **sugars** that are **fermented** by **yeast**. Simple sugars are scarce in nature; they occur in ripe fruit, honey, tree sap, milk, and a few other natural products. The other factor is that the skins of fruits usually harbor yeast, **microorganisms** that get **energy** by converting simple sugars to **carbon dioxide** and ethanol.

Neither of these factors applies to beer, an alcoholic beverage derived from **starch**. Starch is a storage **carbohydrate** consisting of complex chains of hundreds of sugar units; yeast cannot ferment it. The usual source of starch is seeds of **grain**, which typically have less than 2% sugar. Grain and other low-sugar plants do not harbor yeast. Before fermentation, the starch chains must be broken down to sugar by **reaction** with water. **Enzymes** (or extreme chemical treatment) are needed to bring about the reaction. The necessary enzymes are available in human saliva or in sprouted grain, called **malt**. The saliva process is difficult to run on a large scale, so beer-making of moderate to large scale depends on the malt process (or an alternative **mold**-based process used for rice beer, e.g. **sake**). To make beer by the malt process, the live seeds are soaked in water and allowed to sprout. This brings the sugar content to nearly 20% based on dry weight. The sprouted seeds are crushed and treated with warm (not boiling) water. The liquid product has a sugar content equivalent to 60-70% of the weight of the original grain. The sugary liquid is added to a container with yeast, which comes from a previous batch or from added fruit. After a few days of fermentation, the beer is ready to drink.

We can devise a scenario that plausibly accounts for how this process could have been discovered. The cook goes to get grain from the storage pit

for the family's meal, but finds that someone allowed the seeds to get wet and they had sprouted. After uttering some sharply worded commentary, the cook grinds the seeds anyway and adds hot water to make porridge. Surprisingly, the mixture is sweet! It was known from experience that a sweet substance can often be fermented to produce an alcoholic beverage. The cook puts some of the porridge into the fermentation **calabash**. Four days later a not-very-tasty, but moderately intoxicating beverage emerges. After a few batches, the technique is refined, the **flavor** is improved, and the whole village has beer as a reliable intoxicant.

Now we leave aside speculation and consider actual archaeological findings. Evidence was discovered in Raqefet cave in Mount Carmel in present-day Israel that beer was being made from malted **cereal** grain (seeds of grassy plants) as early as the Upper **Paleolithic** period, 13,000 years ago. This is long before **agriculture** was practiced, so it must have been difficult to gather enough grain for a batch of beer. Agriculture, which is the intentional cultivation of a desired species, in this case cereal grain, is needed to provide a consistent supply of beer. Because grain does not harbor the yeast needed for alcoholic fermentation, many grain-based prehistoric fermented beverages were supplemented with fruit or honey. The earliest chemical evidence of such a mixed beverage comes from eight or nine thousand years ago in Jiahu, Henan province, a **Neolithic** site in the Yellow River Valley. Analysis of the contents of some of the earliest pottery ever found revealed a beverage formulated from rice, fruit (grapes or berries), and honey. The earliest chemical evidence of **barley** beer comes from excavations at a prehistoric town, called Godin Tepe, located on what eventually became the Silk Road in the Zagros Mountains in western Iran (Fig. 1.1 site 5). Pottery jars from 5500 years ago contained calcium oxalate (CaC_2O_4), a signature of barley beer production.

The first known written language (although not necessarily the first use of written symbols) came from **Sumer** [SOO mer], a civilization of city states in southeastern **Mesopotamia** (now Iraq) at the downstream end of the Tigris and Euphrates Rivers (Fig. 1.1 site 7). The earliest writing, from about 5400 years ago, was utilitarian, mostly recording transfers of goods. Sumerian and other Mesopotamian languages were written with symbols, called **cuneiform**, that were made with a wedge-shaped stylus pressed into moist clay tablets (Fig. 1.2). Dried clay is durable; many ancient cuneiform documents survive and have been translated. Some of the earliest of these record the production, consumption, and transportation of beer. These tablets document a fully mature **brewing** culture, showing that beer was old when writing was new. One famous cuneiform tablet from 3800 years ago has a poem called *Hymn to Ninkasi*, a poem of praise to the Sumerian goddess of beer. The *Hymn* has a poetic, but not completely comprehensible account of how beer was made. The Sumerians made beer from **bappir**,



Figure 1.1 Locations of sites. *Source:* Modified from The World Factbook. CIA. <https://www.cia.gov/library/publications/the-world-factbook/docs/refmaps.html>



Figure 1.2 Cuneiform Sumerian-Akkadian dictionary of brewing terms. Metropolitan Museum of Art, New York.

and malted emmer wheat and barley, and flavored it, perhaps with honey. Most sources hold that *bappir* was a type of bread, but evidence for this is scant and some scholars are not convinced. Residues from food-making processes in ancient Sumer seldom survive in the humid climate. Sumerian documents mention beer frequently, especially in the context of temple supplies. Beer was also considered a suitable vehicle for administering medicinal **herbs**.

Babylon and Egypt

Dominance over the Mesopotamian region passed back and forth among the Sumerian cities until they were conquered by Sargon of Akkad about 4300 years ago. Akkad was somewhat up-river from Sumer, sharing the same culture, but speaking a different language (Fig. 1.1 site 9). Akkadian dominance lasted about 250 years, after which was a period of smaller-scale kingdoms that seldom lasted much more than 100 years. Around 3800 years ago, the Amorites under Hammurabi of Babylon briefly unified much of Mesopotamia. Babylon was a city on the Euphrates, up-river from Sumer (Fig. 1.1 site 4). Beer made from barley or **emmer** (*Triticum turgidum*, an ancient form of **wheat**) was a staple of the Babylonian diet. After Babylon, Assyria (Fig 1.1 site 7) ruled the Middle East from its two capitals, Assur and Nineva. The Assyrians were displaced by a second wave of Babylonians, among whom was Nebuchadnezzar, the conqueror of Jerusalem. Throughout all this warfare, these cultures continued the brewing tradition of Sumer.



Figure 1.3 Ancient Egyptian tile: grinding grain to packaging beer. Carlsberg-Israel Visitor Center, Ashkelon, Israel.

It is believed that brewing may have spread from the Mesopotamian region to Egypt, about 800 miles (1300 kilometers) away in Africa, but it is also possible that Egypt was first and Sumer later. Evidence of large-scale beer brewing 5500 years ago has been discovered in Nekhen (Hierakonpolis) in the Nile River plain (Fig. 1.1 site 8). Beer was the primary beverage in Egypt at all levels from the Pharaoh to the peasants. The dead were buried with supplies of beer. Mourners of deceased nobles brought offerings of beer to shrines in their tombs. There are many pictures and sculptures of brewing in ancient Egypt (Fig. 1.3). Modern scholars disagree on what these images tell us about the details of ancient Egyptian brewing methods. Microscopic examination of bread and beer residues indicate that, although baking and brewing are usually depicted together, Egyptian beer was not made from bread.

Beer in Asia Minor

The piece of Asia to the north of the Mediterranean Sea and south of the Black Sea is called Asia Minor or Anatolia. The people living there in ancient times were known as Hittites or Hattites. Asia Minor includes most of the Asian part of modern Turkey. It is the homeland of several of the earliest domesticated **crops**, including wheat, lentils, and chickpeas, but not barley. Asia minor was dominated by the Hittite empire from about 4300 years ago to about 3200 years ago. There is ample evidence that they used bread and beer in their rituals, which makes it likely that they also consumed them regularly. There are depictions of people drinking through tubes, suggesting that the beverage was beer. The tubes would have filtered

solid materials from the beverage. Ancient beer had bits of grain and yeast; beer drinking vessels often served as strainers.

Asia Minor has been home to many peoples at different times, including Phrygians, Lydians, Armenians, Galatians, and many others. All of these peoples had active beer cultures. Although it is not known how the Anatolians learned to brew beer, they had a good deal of contact with the Mesopotamian and Canaanite peoples as attested by the Biblical story of the migration of Abraham from Ur in Sumer to Haran in Asia Minor, and then to Canaan.

Phrygia was a kingdom in central Asia Minor (Fig. 1.1 site 3), remembered today because of the legend of King Midas, who is said to have been granted the golden touch. The historical King Midas ruled around 2760 years ago. He is credited with building a huge mound of earth in the Phrygian capital of Gordion as a tomb for his father, King Gordias. The tomb was excavated in 1957; it contained the skeleton of the king, along with the implements of a huge feast. The larger vessels still contained remnants of food and beer, perhaps to serve the king on his journey to the afterlife. This collection includes the largest assemblage of drinking vessels ever uncovered. Figure 1.4 shows a bronze **omphalos** (Greek: bellybutton) bowl. The raised bump corresponds to a depression in the bottom that served as a grip for the fingers. These are the beer mugs of the ancient world.

Beer in Europe

Little is known about the introduction of beer to Europe. Classical Greek and Roman writers were aware of beer in Egypt and in the tribal regions of Europe; most of them had a low opinion of it. Europeans were certainly



Figure 1.4 Phrygian bronze omphalos from Gordion. *Source:* Photograph by Tom Stanley courtesy of Penn Museum. From the collection of the Museum of Anatolian Civilizations, object no. 19068.

capable of inventing beer. There is fragmentary evidence, especially from Scotland, of Neolithic mixed alcoholic beverages containing fruit, honey, and grain. The Neolithic village of Skara Brae in the Orkney Islands off Scotland (Fig. 1.1 site 1) has yielded what some interpret as evidence of beer brewing 3500–4000 years ago. Another indication is that elaborate pottery cups, called **beakers**, are found over a wide range in northern Europe. These include corded beakers (decorated by wrapping the clay with string) and bell beakers (look like an inverted bell) originating from 4900–4300 years ago. Cups suggest drinking; elaborate cups suggest ceremonial drinking of something significant, possibly beer.

Beer could have been introduced to Europe by the Phoenicians, a seafaring nation based in what is now Lebanon. They traded and settled in Europe, especially in what is now Spain and the islands of Sicily and Sardinia. The weak link in this idea is that there is little evidence that the Phoenicians drank beer. Ironically, although they brought writing to the Mediterranean region, their own records did not survive. Another group that could have transmitted the culture of beer are the Celts, whose homeland was France and Germany. Celtic settlers in the Levant, called Gallatians, may well have maintained contact with those who remained in Europe. This could have been a route of entry for Levant beer culture to Europe. Roman historians record beer drinking among Celts in Gaul (France/Belgium) 2400 years ago, and among German tribes in the first century CE (1900 years ago).

Historical records from northern Europe before the **Middle Ages** are incomplete or missing. The original Neolithic crops, such as wheat and barley, did not originate in Europe. Finds of possible brewing in Scotland, 3000 miles (4800 km) from Sumer with little in between, suggest that Europeans may well have invented brewing independently. The Old English epic *Beowulf*, which was written some time around 1000, is set in a militaristic Danish culture whose warriors seal their loyalty to their king during elaborate feasting and drinking of beer and **mead**, an alcoholic beverage made from honey.

Beer brewing, like other technologies, started at the household level, where it was a kitchen chore. The scale of brewing advanced in stages from the individual level, first as households selling extra beer, then as collections of households sharing equipment, then as multiple workers in the same building. By the 600s and 700s, larger-scale brewing in landed estates and monasteries developed. The techniques of large-scale beer brewing by specialized workers were developed largely in monasteries. Commercial brewing arose in Belgium and Holland between 1100 and 1300.

Monasteries

European **monasteries** played a key role in the development of modern beer. St. Benedict (480–547) of Nursia in Italy wrote a set of monastic rules