SECOND EDITION

MASTERING BREWING SCIENCE

Quality and Production

Matthew Farber · Roger Barth

with website

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Second Edition

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data
Names: Farber, Matthew, 1951- author | Barth, Roger author
Title: Mastering brewing science : quality and production / Matthew Farber, Associate Professor of Brewing Science, Rowan University, New Jersey, USA, Roger Barth, West Chester University, West Chester, PA, US.
Description: Second edition. | Hoboken, New Jersey : John Wiley & Sons, Inc, 2025. | Includes bibliographical references and index.
Identifiers: LCCN 2024060680 (print) | LCCN 2024060681 (ebook) | ISBN 9781394206995 paperback | ISBN 9781394207008 adobe pdf | ISBN 9781394207015 epub
Subjects: LCSH: Brewing–Textbooks
Classification: LCC TP570 .F33 2025 (print) | LCC TP570 (ebook) | DDC 663/.3–dc23/eng/20250227
LC record available at https://lccn.loc.gov/2024060680
LC ebook record available at https://lccn.loc.gov/2024060681

Cover Design: Wiley
Cover Image: Courtesy of Naomi Hampson

Set in 10/12pt STIX Times Ten LT Std by Straive, Pondicherry, India

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PREFACE

Brewing is a creative art. Underlying that art is a framework of technical knowledge, mostly in chemistry and biology, but with significant contributions from physics and engineering. To make five gallons of drinkable beer requires little scientific background, with the definition of *drinkable* up for debate. To make hundreds of batches of beer, each of which meets the expectations of the customers, each of which is consistent with the last, sound science is required. This is the goal of modern brewers.

This book is written as an instructional resource for teaching or learning brewing practice and theory with a focus on the underlying science. We try to strike a balance between critical scientific concepts, beer production, and day-to-day practical issues in beer quality. By understanding the science of beer production, readers will be better equipped to troubleshoot problems in the brewery, one of the most critical skills for a successful career in beer. We have produced hundreds of illustrations to demonstrate key concepts and to demonstrate the numerous pieces of equipment commonly used in breweries. Unlike drawings provided by equipment suppliers, our drawings do not inform operation or maintenance. Rather, they illustrate essential design elements and concepts as they pertain to the process.

As more and more brands crowd the shelves, the consumer has more and more options. If one batch of beer is flawed in the eyes (and palate) of the consumer, it is easy to move on to another brewery. Brewing with quality requires a high level of awareness of the procedures, the materials, and the equipment used in brewing. Our goal in this book is to address essential concepts in quality and consistency to help the readers become better brewers. At the conclusion of each chapter are review questions to check for understanding and one or more case studies for critical analysis and discussion.

In this book, we first introduce a high-level view of the brewing process. Then we dive into the fundamentals of biology and chemistry with appropriate application to the brewing process. These concepts will be critical to better understanding of subsequent chapters. The remaining material is presented in order, from raw materials, through the brewing process, and on to methods for quality. All employees at a brewery should be trained in basic concepts of quality. Quality is best managed at the source where response time is quick.

New material in this edition includes expanded coverage of water, malt, hops and yeast, each in its own chapter. The yeast chapter includes coverage of yeast hybridization and PCR. Specific safety issues are covered with the operations to which they are relevant. Safety issues that apply to more than one process or location are covered in Chapter 15, Good Brewery Practice. This chapter also includes suggestions for effective standard operating procedures (SOPs) and the material previously covered in "Mathematics of Quality." Chapter 19, Beer-Related Products and Processes, is entirely new. It covers non/low alcohol beer, gluten-free beer, flavored malt beverages, hard seltzer, hemp beer, high-gravity brewing, and brewing with bacteria. In addition, most of the end-of-chapter problems are new or revised. A companion website provides additional resources.

We make extensive use of primary and secondary references, but we deliberately omitted in-line references and any citations that might be distracting to the student. Useful and critical references are mentioned at the end of each chapter under "Bibliography." Many of the facts that we present were won by the brilliant insights and very hard work of thousands of scientists and brewers. We herewith acknowledge their contributions, even if, for the benefit of readers, we did not give them citations. We hope that this approach will be more effective than voluminous citations in putting the work of our colleagues into the hands of students, who will be the next generation of brewers and brewing scientists.

ACKNOWLEDGMENTS

We gratefully acknowledge our wives, Dr. Grace Farber and Marcy Barth, for their love and support. Marcy provided outstanding expertise and artistry in the photography, design, and execution of illustrations. Grace provided guidance and advice in the teaching of essential concepts in biology. Our children and grandchildren (eight and counting between the two of us) are a source of inspiration. We humbly thank our families for their patience, encouragement, and love.

Donna-Marie Zoccoli, our eagle-eyed copy reader, read the manuscript multiple times, corrected errors, and made countless suggestions that make the book easier to read and understand. Dr. Naomi Hampson and Marcy Barth took outstanding photographs of equipment and instrumentation. Kent Pham, Dave Goldman, Michelle McHugh, and Eric Jorgenson provided micrographs. We are pleased to gratefully acknowledge expertise and guidance provided by Tony McCrimmon, Brewery Safety Consultant for the coverage of safety in Chapter 15 and throughout the book. Our friends at Bonesaw Brewing, Deer Creek Malt House, Imperial Yeast, Levante Brewing, Philadelphia Brewing, Sly Fox Brewing, Susquehanna Brewing, Victory Brewing, Yards Brewing, and Yuengling and Sons were generous with their time and gave us insights, explanations, and access for photographs. Our professional societies, The American Society of Brewing Chemists (ASBC) and the Master Brewers Association of the Americas (MBAA) maintain outstanding resources and networking opportunities that were critical to our own development as brewing scientists. Our institutions (Rowan University and West Chester University) and their libraries and librarians provided essential support. Our editors at Wiley, Jonathan Rose, Neena Ganjoo, and Durga Thiyagarajan have been supportive, helpful, and responsive. Our students motivated the entire project with their enthusiasm and unquenchable desire to learn.

We are forever grateful to the supporting words and actions of our own teachers and mentors in years past. Dr. Farber acknowledges Dr. Peter Berget for his mentorship and Dr. Angela Weisl for the inspiration to pursue writing. Dr. Farber is incredibly thankful for his parents, Larice Farber and the late Dr. Phillip Farber, for instilling endless curiosity and creativity in him. Dr. Barth acknowledges his physical chemistry teacher and father, the late Dr. Max Barth; his high school chemistry teacher, Mr. Dugan; and his high school English teacher, Mr. Martini, who taught the importance of clarity and precision in writing.

ABOUT THE AUTHORS

Matthew Farber, PhD, was awarded a BS in biology from Seton Hall University and a PhD in molecular and cellular biology with a minor in teaching from the University of Pittsburgh. In 2015 he was the founding director of the Brewing Science certificate at the University of the Sciences in Philadelphia, Pennsylvania, USA. He is now an associate professor of Brewing Science at Rowan University in Glassboro, New Jersey, USA. His research interests include innovative applications of biotechnology for the improvement of fermented food and beverages, with a focus on applied microbiology and beer quality. He is the primary inventor on four patents including discovery of *Philly Sour*™, a novel yeast used for sour beer production, and the creation of *Farber Pham Diastaticus Medium*, a selective medium for the isolation of yeast contaminants. He is an active member of the American Society of Brewing Chemists, and he serves on the governing board of the Philadelphia District of the Master Brewers Association of the Americas.

Roger Barth, PhD, was awarded a BA in chemistry from La Salle College, Philadelphia, Pennsylvania in 1973, and a PhD in physical chemistry from the Johns Hopkins University, Baltimore, Maryland, in 1977. His post-doctoral work at University of Delaware and Drexel University involved industrial catalysis. He was a faculty member in the chemistry department at West Chester University of Pennsylvania from 1985 until his retirement in June 2021. He created a university course entitled *The Chemistry of Beer* and is the author of its textbook. Barth's research focus is brewhouse processing and beer, wort, malt, and hops analytical methods. He is author, coauthor, or editor of five books and five refereed book chapters. He is a member of the American Chemical Society, the American Association for the Advancement of Science, the American Society of Brewing Chemists, and serves on the Editorial and Publications Committee of the Master Brewers Association of the Americas.

ABOUT THE COMPANION WEBSITE

The companion website for this book has several resources that readers can access.

www.wiley.com/go/MasteringBrewingScience_2e

- An Excel™ workbook with eight sheets to facilitate calculations.
  - Total package oxygen (TPO): Enter the temperature, mass of beer, headspace volume, dissolved oxygen shaken, and dissolved oxygen unshaken. Total package and headspace oxygen will be calculated.
  - Carbonation: Enter temperature and desired carbonation volume. Carbonation pressure will be calculated. Enter temperature and carbonation pressure. Carbonation volume will be calculated.
  - Strike temperature: Enter desired mash-in temperature, malt initial temperature, liquor-to-grist ratio, and grist percent moisture. Strike temperature will be calculated.
  - Decoction: Enter desired final temperature, cold and hot temperatures, and total amount (cold + hot) of mash. Amount of mash to be heated to the hot temperature will be calculated.
  - Original or apparent extract: Enter the specific gravity. Extract (original for wort, apparent after fermentation) will be calculated.

  - Wort specific gravity: Enter wort extract (degrees Plate) specific gravity will be calculated. Only works for wort with no alcohol.
  - Extract and attenuation from specific gravity: Enter original and final specific gravity. Original extract, apparent extract, real extract, real attenuation, ABV, and ABW will be estimated.
  - Dilution: Enter extract of high gravity wort, volume of HG wort, and desired extract of diluted wort. Volume and mass of water to add, volume and mass of diluted wort will be calculated.

- End of Chapter problem solutions.
- Links to useful videos.
- Standard Operating Procedure Example.
- PowerPoint Slides of all numbered figures.

Overview. Bonesaw Brewing Co. Glassboro, NJ. Photo: Naomi Hampson.

CHAPTER 1

BREWING QUALITY OVERVIEW

We wrote this book to help you better understand, appreciate, and apply the science behind the materials and processes of making **beer**. The better your grasp of **brewing** science, the more dependably you will be able to make delicious beer, and the more reliably you will be able to devise new beers to meet changing consumer preferences. So what is beer? How does beer differ from its **fermented beverage** brethren? The US legal definition is given in Section 19.3: "Flavored Malt Beverages"; a commercial definition encompasses the wide variety of products that are included in beer marketing, but in a book on brewing science, we will use a scientific definition. Beer is an **alcoholic beverage** derived from a source of **starch** without concentrating the alcohol content. "Derived from" covers a complex series of interacting steps, each of which influences the character of the final product and is ultimately the focus of this book. Brewing beer differs from **fermentation** of **wine** in that for brewing, a source of starch must first be converted into fermentable **sugars**. The brewer is responsible for management and control of all steps of the brewing process to produce a beer of reliable and reproducible quality.

There are four main ingredients in beer: water, **malt**, **hops**, and **yeast**. If randomly combined, these four ingredients might turn into an alcoholic beverage of questionable quality, but in this chemical process, the brewer is like a **catalyst**, a substance that guides and speeds up a **reaction**. Mastering

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the science of raw materials and the process steps of beer production is essential to making quality beer. We will start with a broad overview of the brewing process followed by a scientific history of beer and the scientific method. In learning how to conduct an experiment, you will begin to understand the process of troubleshooting problems in the **brewery**. Finally, as our major goal is to brew beer of excellent quality and consistency, we will discuss beer quality as defined in several contexts. Each of these topics will be discussed further in depth in the chapters that follow.

1.1 INGREDIENTS

In addition to the main ingredients, beer may be brewed with **adjuncts** and **processing aids.** Adjuncts are sources of starch or **sugar** other than malt. Processing aids are materials used to help give the beer desirable characteristics. Some common processing aids are **filtration media**, **finings**, carbon dioxide, **foam** enhancers, and coloring materials. In this overview, we will touch upon the main four ingredients. Adjuncts and processing aids are covered in later chapters.

Water

Beer is usually more than 90% water. Beer production can take as much as 12 volumes of water to make 1 volume of beer. Some breweries have been able to cut this ratio to three or less. Less water means less **energy** use, less wastewater for disposal, and less negative impact on the environment. Pure water is a characterless **compound** of fixed composition. It is supplied to breweries as a **mixture** with many **components** present in trace amounts. The nature and **concentrations** of these trace components are important to the character and quality of the beer. Water is usually modified to adjust the trace components. Water that is to be made into beer is sometimes called **brewing liquor**. Chapter 4 discusses brewing water in detail.

Malt

Brewing beer requires starch, which is usually derived from **cereal grain**. Malt is prepared from seeds of cereal grain by **steeping** (soaking in water), **germinating**, and drying. The malting process produces **enzymes** that convert starch to fermentable sugars. The most common grain for malting is **barley** (***Hordeum vulgare***), but wheat, rye, and oats can also be malted. Rice and **maize** (corn) can also be used as sources of starch for brewing but require special treatment. Since medieval times, malting has been a separate craft from brewing, requiring specialized facilities. Nonetheless, brewers need a basic understanding of the malting process to fully understand and apply malt as a raw material. Malt and malting will be discussed in Chapter 5.

Hops

The **hop** (***Humulus lupulus***) is a climbing plant, more specifically a **bine**. The fruits of the hop plant, hops, are boiled with the beer **wort** to provide bitterness and other flavors. Hops may also be added to the fermenter in a process called **dry hopping**. Hop compounds provide an antibacterial effect to help preserve the beer. There are many varieties of hops with different flavor profiles, as well as advanced hop products that can be easier to use than natural hops. Chapter 6 provides details about hops and their processing.

Yeast

Yeast is a single-cell **fungus** that converts sugar to **ethanol** and carbon dioxide. The action of yeast on sugar is fermentation. Most beer fermentation is carried out by one of two species of yeast: ***Saccharomyces pastorianus***, used for **lager beer**, and ***Saccharomyces cerevisiae***, used for **ale**. Some specialty beer styles are fermented with ***Brettanomyces*** *bruxellensis*, *Brettanomyces lambicus*, or related species. Within a particular yeast species, there are many variations, called **strains**. The species and strain of yeast affects the flavor and character of the beer. Yeast may be cultivated at the brewery or **pitched** directly from wet or dry commercial products. Processes and practices involving yeast are covered in detail in Chapters 10 and 11.

1.2 BREWING OVERVIEW

A graphical overview of the brewing process is provided in Figure 1.1. In brief:

- Malt and other grains are crushed in the **mill**. Crushed grain is called **grist**.
- The grist is loaded into the grist case until mashing.
- The grist is mixed with hot water in the **premasher** on its way into the **mash tun**.
- In the mash tun, enzymes from the malt cause the starch in the grist to be converted to soluble **extract**, which contains sugars that the yeast can ferment.
- The solution of extract, called wort, is separated from the remaining grist particles in the **lauter** tun. Extract that sticks to the particles is washed out with hot water in a process called **sparging**.

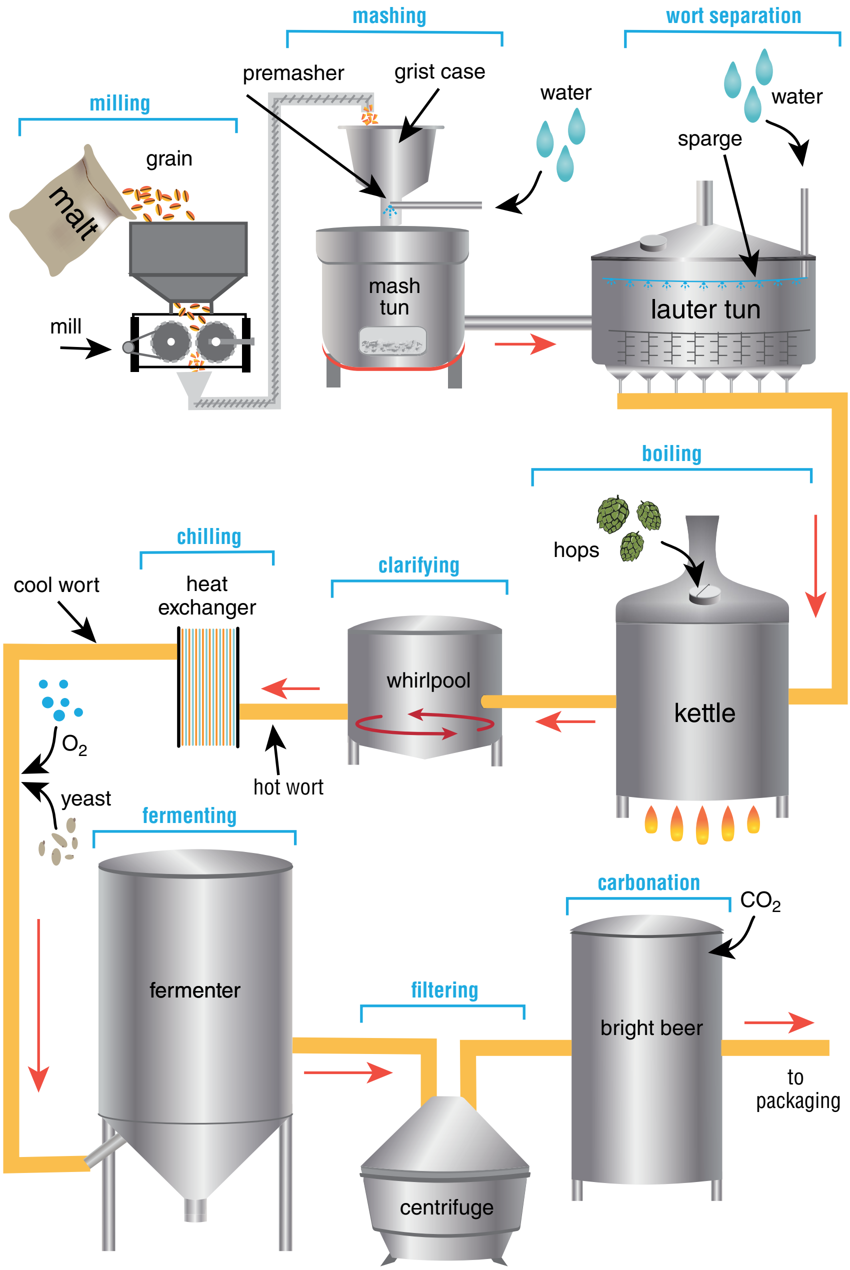

Figure 1.1 Overview of the brewing process in a four-vessel brewhouse.
Source: Drawing: Marcy Barth.

- The clear wort is boiled in the **kettle**. Hops are added.
- The remains of the hops and solids that form during boiling (**hot break** or **trub**) are removed in the whirlpool.
- The clear, boiling-hot wort is cooled in a **heat exchanger** called the wort chiller.
- During **knockout**, oxygen and yeast are added to the cool wort while it is pumped into a fermenter.
- After several days to more than a month of fermentation and **conditioning**, the yeast is removed from the beer, and the beer is pumped into the **bright beer tank**. Separation of yeast and solids may be facilitated by special equipment such as a **centrifuge** or **filter**. Carbon dioxide is added under pressure to provide the characteristic lively mouthfeel.
- The beer is served directly from the tank or packaged into secondary containers.

A summary of the duration and temperature ranges for each step in the brewing process is provided in Table 1.1. This table represents a general summary and overview; different breweries using different equipment and brewing different styles of beer may have quite different programs.

Milling

Malt is delivered to breweries in bulk (loose in a truck or rail car), in **super sacks**, or in bags. Malt must be milled, that is, crushed into small pieces to expose the starch, before it is used for brewing. Crushed grain is called grist. The device that performs the operation is a mill (Figure 1.2). The primary purpose of milling is to allow starch from the grain, enzymes from malt, and water to come into contact during the mashing step. A seed of grain is protected by a water-resistant **seed coat**, and a woody shell

TABLE 1.1 Brewing Steps, Durations, and Temperatures

Process Step	Duration	Temperature	
Milling	1–2 hours	Ambient	
Mashing	1–2 hours	45–67 °C	(113–153 °F)
Lautering/sparging	1–2 hours	75–78 °C	(167–172 °F)
Boiling	1–2 hours	105 °C	(221 °F)
Whirlpool	15–30 minutes	74–76 °C	(165–169 °F)
Fermentation (ale)	4–10 days	15–25 °C	(59–77 °F)
Conditioning (ale)	at least 1 day	−1 to 6 °C	(30–43 °F)
Filtration	2–12 hours	2–6 °C	(36–43 °F)
Packaging	<12 hours	2–6 °C	(36–43 °F)
Duration of typical shelf life	~6 months	Ambient	

Figure 1.2 Mill at Susquehanna Brewing Company. *Source*: Photo by Naomi Hampson.

called the **hull**. Milling splits the hull, breaks open the seed coat, and crushes the interior of the seed, producing additional **surfaces** where water can react with starch. Milling details affect the character of the beer and the efficiency of the process. It is preferred that the malt hulls be split but not pulverized because they will be needed to aid wort separation later in the process.

Mashing

During the mashing step, starch, which brewing yeast cannot ferment, is converted to smaller sugars that yeast can ferment. During mashing, hot water, sometimes called brewing liquor, is mixed with the grist to give a temperature in the range of 60–70 °C (140–158 °F). Sometimes, mashing starts at a lower temperature, and the temperature is raised continuously or in steps to influence the protein or **carbohydrate** profile. Mashing is conducted in a **mash conversion vessel** (**MCV**), also called a mash tun (Figure 1.3). The MCV may contain an agitation paddle for gentle mixing. The details of the time–temperature profile, the activities of enzymes