Classic Texts in the Sciences

Georg Schwedt
Editor

Justus von Liebig
Organic Chemistry in its Application to Agriculture and Physiology

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1.1 On Liebig's Biography

Justus Liebig was born on May 12, 1803 in Darmstadt as the son of a "materialist" (druggist). After dropping out of preparatory school in 1817/1818, he worked as an apprentice in a pharmacy in Heppenheim on Bergstraße. Instead of completing the apprenticeship, however, he began to study chemistry at the Prussian university founded in Bonn in 1818, under Karl Wilhelm Kastner (1783–1857), whom he followed to the University in Erlangen after Kastner's appointment there.[1] Kastner himself, who had business and personal ties

[1] Schwedt, G.: *Chemische Briefe aus einem Lustschloss. Justus Liebeg als Student im Schloss Clemensruhe in Bonn-Poppelsdorf*, Shaker, Aachen 2012.

G. Schwedt (ed.), *Justus von Liebig*, Classic Texts in the Sciences,
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with Liebig's father, probably cleared the way for a son without a school-leaving certificate to study. The young University of Bonn was probably more liberal than universities with a longstanding tradition behind them. His membership in a forbidden fraternity and participation in student demonstrations in Erlangen led to him being forced to leave the city and return to Darmstadt in 1822. On Kastner's recommendation, he was able to resume his studies in Paris with a scholarship from Grand Duke Ludwig I of Hesse-Darmstadt (1753–1830), where he attended lectures by Dulong, Thénard, and Gay-Lussac, among others. Liebig continued to pursue his investigations on fulminating mercury there and isolated fulminic acid. Gay-Lussac presented Liebig's investigations on July 28, 1823, at a meeting of the Paris Academy of Sciences. Alexander von Humboldt also attended this meeting and subsequently recommended Liebig to Grand Duke Ludwig I for a professorship at the University of Giessen. Liebig had meanwhile been conferred a doctoral title at the University of Erlangen in absentia.

On May 24, 1824, Liebig, at just 22 years of age, was appointed supernumerary professor (*Extraordinarius*)—and then in 1825 full professor (*Ordinarius*)—of chemistry at Giessen. On lecture tours in France and England, he also gained international renown. In Giessen, he transformed a former guardhouse into a teaching and research laboratory (Fig. 1.1) that attracted students from many countries.[2] In 1831, he developed his five-bulb apparatus for quantitative elemental analysis, which will be described in detail later. It was to become one of the prerequisites for the rapidly developing field of organic chemistry of his day. In 1837, he reported on the state of organic chemistry and analytics in England at the invitation of the British Association for the Advancement of Sciences in Liverpool.

In 1840 his book *Organic Chemistry and Its Applications to Agriculture and Physiology* appeared. With this work—supported by his findings from quantitative analysis—Liebig founded agricultural chemistry. In this book, he formulated, among other things, his ideas about a carbon cycle and postulated his 'law of the minimum' with regard to optimal plant nutrition.

In 1852, Liebig was appointed to the University in Munich, where he mainly continued his research in applied organic chemistry—such as the deacidification of rye bread, on baking powder, infant food and meat extract—"a new meat broth for the sick," bearing his name: "Liebig's Extract of Meat" (which is still available today). One of the first biographies of Liebig was written by his student and assistant Jacob Volhard (1834–1910, who became professor in 1869 at Munich then Erlangen and finally from 1882 to 1908 at Halle).[3] At Munich, Liebig was able to oversee the building of a new institute, introduce public lectures with demonstration experiments there and continue to write books (Fig. 1.2).

[2] Schwedt, G.: *Liebig und seine Schüler*, Springer, Heidelberg 2003.

[3] Volhard, J.: *Justus von Liebig*, Barth, Leipzig 1906. Further biographies: Kohut, A.: *Justus von Liebig. Sein Leben und Wirken*. "Based on the best and most reliable sources," second ed., Roth, Giessen 1906. Strube, W.: *Justus Liebig. Eine Biographie*, Sax, Beucha 1998. Brock, W.H.: *Justus von Liebig. Eine Biographie des großen Wissenschaftlers und Europäers*, Vieweg, Braunschweig 1999.

Fig. 1.1 Chemical Laboratory of Gießen, (© Archivist/stock.adobe.com)

1.2 Agricultural Chemistry in History

The earliest accounts of the use of organic fertilizers in agriculture or for plant nutrition can already be found in antiquity. The Babylonians used stable manure and slurry as well as compost; the Egyptians used mud left behind by the Nile floods, which contains both minerals and organic substances. Around 800 BC, Homer mentioned in his *Odyssey* cow dung serving as a fertilizer, and Pliny the Elder (23–79 AD) described in his work *Naturalis historia* green manuring by Romans, who among other things plowed under legumes like broad beans. The insights about plant nutrition also provided the foundations for the optimal use of fertilizer.[4, 5] In 1620 Johan Baptista van Helmont conducted vegetation experiments with water as a nutriment. In 1770, Carl Wilhelm Scheele recognized that plants produce carbon dioxide. Joseph Priestley found in 1775 that plants also excrete oxygen, and Jan Ingenhouz was able to determine experimentally in 1779 the influence of light on gas metabolism in plants. Nicolas Théodore de Saussure offered the first quantitative explanation for photosynthesis in 1804.

Antoine Laurent de Lavoisier (1743–1794), whose historical activities in chemistry mark the beginning phase of chemistry as a science, also already dealt with agronomic

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[4] Brock, W. H.: *Viewegs Geschichte der Chemie*, Braunschweig and Wiesbaden 1997.

[5] See note 1.

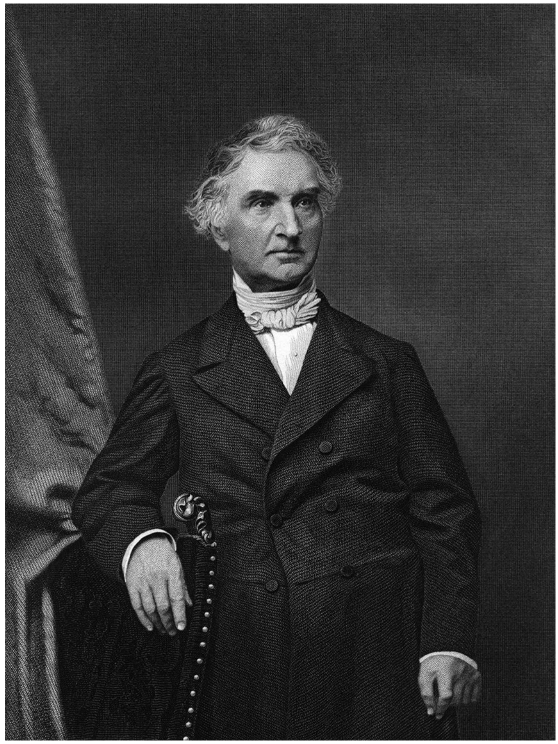

Fig. 1.2 Portrait of Liebig. (© JT Vintage/Glasshouse Images/picture alliance)

experiments on his estate in his role as a "practicing farmer." Through the cultivation of fodder plants (legumes) he created the prerequisite for an increase in livestock and thus also for the production of natural fertilizer.[6] Humphrey Davy (1778–1829) is also counted among the precursors of Liebig's agricultural chemistry from the field of chemistry. His eight lectures titled 'Elements of Agricultural Chemistry' were held before the British Board of Agriculture and a German edition appeared in 1814 under the title *Elemente der Agriculturchemie* …—with prefatory notes by Albrecht Thaer. Davy's lectures also inspired Sigismund Hermbstaed (1760–1833) to publish his *Archiv der Agrikulturchemie* from 1803 to 1818 in which he edited and commented on publications from all over Europe. And finally, the term *agricultural chemistry* was also used by the Erfurt pharmacist Johann Bartholomäus Trommsdorff (1770–1837) in the title of his textbook *Anfangsgründe der Agrikulturchemie* (1816), adopting the chapters on plant nutrition, soil science and fertilizer theory.[7]

[6] Schwenke, K. D.: Lavoisier und die Anfänge der Agrikulturchemie, in: *Mitteilungen der Gesellschaft Deutscher Chemiker/Fachgruppe Geschichte der Chemie* 22 (2012), 20–36—with detailed references.

[7] See note 6.

1.3 On Liebig's Forerunners

1.3.1 Johan Gottschalk Wallerius

In 1761 Johan Gottschalk Walerijs (1709–1785) published his *Agriculturae Fundamenta Chemica,* which is considered as a first milestone in the history of agricultural chemistry—in other words, "as the first comprehensive example of conceptual agrochemical research."[8]

Wallerius was a Swedish chemist as well as metallurgist and mineralogist. He studied mathematics, physics and medicine at the University of Uppsala from 1725, took his master's degree in the faculty of philosophy in 1731, continued his medical education in Lund and earned his doctorate in medicine in 1732. In 1749 he received the newly established chair for chemistry, metallurgy and pharmacy at the University of Uppsala. In 1751 he coined the terminological distinction between "pure" and "applied" science—in chemistry, as: *chemia pura* versus *chemia applicata.* In 1767 he had to give up teaching due to a chronic illness, retired to his country estate near Alsike (in the Province of Uppsala, the major town of the municipality Knivsta) and began to occupy himself intensely with agricultural issues (Fig. 1.3). He published his observational findings "made in agriculture over the course of 30 years" (*Beobachtungen bei der Landwirtschaft durchgeführt über 30 Jahre, 1747–1777*).

Johann Friedrich Gmelin (1748–1804), professor in Göttingen from 1773, applauded Wallerius's *Agrikulturchemie* from 1761 in his 'History of Chemistry':[9]

"Even in agriculture, principally in tillage, people began to apply chemistry, to judge from the nature of the soil the influence of the ground on the flourishing of plants and to seek therein the means for improvement; the Uppsala teacher J. G. Wallerius not only endeavored to demonstrate what each constituent of plants contributes toward their growth, … trace down … the cause of infertility of fields, and the influence of salty and clayey soil on fertility, but he also outlined chemical principles of field cultivation, which are based on the nature of the various constituents of plants and on the properties of the soil in which the plants are set, and sought therein the means to improve soil."

Hahn characterizes Gmelin's description as "a conception by Wallerius programmatically oriented toward the application of chemistry to agriculture."[10]

This concept proceeds from the assumption that the basic substances making up a plant's body as known from the literature first be considered, along with self-conducted chemical investigations. He identifies these as water, earth, salt and oil. He then includes

[8] Hahn, Ch.: Eine frühe Konzeption der Agrikulturchemie: Johan Gottschalk Wallerius' *"Agriculturae Fundamenta Chemica"* (1761), *Mitteilungen der Gesellschaft Deutscher Chemiker/Fachgruppe Geschichte der Chemie* (Frankfurt/Main), Vol. 25, 57–73, 2017 (further references there).

[9] Gmelin, J. F.: *Geschichte der Chemie seit dem Wiederaufleben der Wissenschaften bis an das Ende des 18. Jahrhunderts*, Göttingen 1799, Vol. 3, p. 3.

[10] See note 8.

Fig. 1.3 Portrait of Wallerius

the air as a plant nutrient. As fertilizer, he defines substances that contain fat and/or water. From his approaches there results a kind of soil cultivation doctrine: Each soil should be plowed, mixed, fertilized according to its chemical and physical composition to the extent that it can absorb sufficient nutriment from the air and retain it.

Hahn finally states that this "conception of a doctrine of plant nutrition was (still) [based] on foundations and manners of thinking in chemistry which were to be fundamentally revised, indeed completely discarded two decades later."[11]

Wallerius described a qualitative concept, without being able to cite quantitative analyses. Nevertheless, his work was widely distributed in the second half of the eighteenth century into the first quarter of the nineteenth century, also through translations. The book first appeared in German in 1764 in Berlin, 1765 in Bern, and 1770 in Graz; in French in Yverdon 1766 and Paris 1774; in English 1770 in London; a new edition in Swedish 1778 and the fourth edition of an English reissue appeared 1824.[12]

1.3.2 Albrecht Thaer

Albrecht Daniel Thaer (1782–1828) settled in his hometown Celle as a doctor in 1774 after studying medicine in Göttingen, became city physician in 1778, was appointed electoral court physician in 1780 and began to take an interest in agricultural issues. He joined

[11] Hahn in note 4, p. 68 or 69.

[12] See note 11.

the Royal Hanoverian Agricultural Society in Celle in 1784 and acquired a roughly 32-hectare agricultural estate near Celle by the River Aller. During this time, he was particularly interested in the English specialist literature. His estate developed into an agricultural model farm. Between 1798 and 1804 he published his findings as 'Introduction to the Knowledge of English Agriculture… ' in three volumes.[13] Self-guided educational tours (*Bildungsreisen*) in agriculture took him to the Mark Brandenburg around 1800. In 1804, he moved to Prussia and bought the Möglin estate (near Wrietzen, now with a museum) including the Königshof steading located in the Oderbruch region. His justification for moving to Prussia reads:

"The burdens associated with the French occupation, the refusal to lease the Weende domain near Göttingen, and the solicitation by Minister Hardenberg and the district administrator v. Itzenplitz, prompted him to accept the offer by the Prussian King, Friedrich Wilhelm III."[14] In 1806, Thaer inaugurated his agricultural school in Möglin. Between 1809 and 1812, his main work on 'Principles of Rational Agriculture' appeared in four volumes.[15] In 1810, he was appointed Extraordinary Professor of Cameral Sciences at the newly founded Berlin University. During the absolutist era, the cameral sciences were a practical, i.e., applied discipline encompassing all areas of public administration (Fig. 1.4).

The essential points with reference to Liebig include, among other things:

Soil quality is determined by the composition of the soil (e.g., sand, clay, humus) and the level of fertilizer, referred to by Thaer as the "power of the soil."[16] Plant nutrition also plays an important role in Thaer's works. He already stated in his 'Introduction to the Knowledge of English Agriculture… ': "In order to identify those substances which make up the nutritional parts of organic bodies, we must first get to know the simpler substances of which they consist. According to reliable investigations, these are partly volatile *carbon*, *hydrogen*, *oxygen* and *azote* (nitrogen)—partly solid or fire-resistant earths, alkali, phosphoric base and a little iron."[17]

[13] Digitized: *Einleitung zur Kenntniß der englischen Landwirthschaft und ihrer neueren practisichen und theoretischen Landwirthe und Cameralisten*, Vol. 1, second improved ed., Hannover 1801; second vol. first and second sections, Hannover 1801; third and last vol., Hannover 1804—see Albrecht Daniel Thaer—Wikisource.

[14] Fördergesellschaft Albrecht Daniel Thaer (ed.), exhibition catalog *Albrecht Daniel Thaer. 14.05.1752–26.10.1828*, revised ed. 2002.

[15] *Grundsätze der rationellen Landwirtschaft,* published by Realschulbuchhandlung Berlin 1809–1812—digitized, see Thaer/Wikisource.

[16] „Kraft des Bodens"; see note 10.

[17] Töter, H.: Albrecht Daniel Thaer und die Entwicklung zum modernen Landbau, p. 118; in: Panne, K. (ed.): *Albrecht Daniel Thaer—Der Mann gehört der Welt*. Companion publication to the exhibition of the same name at Bomann Museum in Celle on the 250th birthday of Albrecht Daniel Thaer, Celle 2002—there cited by Schulze, F. G.: *Thaer oder Liebig? Versuch einer wissenschaftlichen Prüfung der Ackerbautheorie des Herrn von Lieben, besonders dessen Mineraldünger betreffend*, Jena 1846.

Fig. 1.4 Portrait of Thaer

In his ‘Principles of Rational Agriculture’ Thaer stated: “Although nature offers us various inorganic materials, which can animate and strengthen vegetation … it is actually only the animal-vegetable manure or that mold (humus) in the right state of decomposability which gives the plants the most essential and necessary part of the nutrients.”[18]

1.3.2.1 On Humus Theory

The humus theory does not originate from Thaer, but he took it up and developed it further. The Greek philosopher Aristotle (384–322 BC) formulated the contention that a plant fed off humus (an organic substance) and that soil fertility depended on the humus content. The universal scholar Jean-Henri Hassenfratz (1755–1827; French mineralogist, physicist, chemist and politician) held the view that a plant did not take its carbon needs from the air, but from the darkly colored humus substances in the soil. Thaer adopted this theory and referred to minerals only as “stimulants” of plant development.

Some of his essential statements can be summarized as follows:

The soil is a mixture of silicate, lime, clay, and bitter earth, to which humus is added as a fifth component. “The vegetal-animal matter, once life has left it, is decomposed by the

[18] Ibid., p. 119 (Thaer (1800), p. 138).

putrefactive fermentation process—if the conditions for it are not otherwise lacking—and the product of this is mold."[19]

The core statement of Thaer's further developed humus theory was that a part of the humus in organic form is the most important nutriment for plants. "The fertility of the soil actually depends entirely on it [humus], because apart from water, it is the only thing that provides food for the plants in the soil." And: "Humus has … less oxygen but more carbon and nitrogen than the plants from which it originated …. It is particularly in constant interaction with atmospheric air …. Humus probably affects vegetation through the production of carbonic gas."[20]

These statements reveal initial quantitative approaches, although he still refers here to analyses by the Swiss naturalist Nicolas Théodore de Saussure (1767–1845). However, it is known that by 1818 his teaching institute already had an agricultural chemical laboratory of its own for soil analyses.[21]

1.3.3 Carl Sprengel

Philipp Carl Sprengel (1787–1859) spent his youth on his father's half-estate in Schillerslage (Burgdorf near Hannover). At 15, he became one of Thaer's first students at the agricultural teaching institute founded in Celle in 1802. He followed Thaer to Möglin in 1804, from whence he left as farming inspector of the Möglin estate in 1808 to work subsequently on estates in Upper Lusatia, Thuringia, Silesia, and Saxony. In the winter months, he also attended lectures on chemistry. From 1817 to 1820, he undertook extensive study tours. Based on his comprehensive practical experience, he was convinced that the latest findings in the natural sciences ought to be applied to agricultural practice. He studied chemistry, physics, botany, mineralogy, geology, and mathematics in Göttingen from 1821 to 1823 and earned his Ph.D., then worked in the laboratory of the chemist Friedrich Stromeyer, in 1826 qualified as a lecturer, and taught agricultural chemistry as a private lecturer. In 1826, he refuted the hitherto prevailing humus theory by demonstrating that its effect was due to the nutrients contained therein, including minerals. After working as a professor at the *Collegium Carolinum* in Braunschweig, he became the general secretary of the Pomeranian Economic Society in 1839 and moved to Regenwalde (now Resiko in West Pomerania/Poland), where he founded a private agricultural teaching institute in 1842 (from 1846 on called *Landbau-Academie zu Regenwalde*), conducted large-scale

[19] Quoted from: Klemm V. and Meyer, G.: *Albrecht Daniel Thaer. Pionier der Landwirtschaftswissenschaften in Deutschland*, Halle (Saale) 1968, sec. 8.2.2 on advocates of the humus theory, pp. 111 ff.

[20] Thaer, A.: *Grundsätze* p. 13, third law, § 112, p. 403 or § 110, p. 402—for the quote see note 17.

[21] See note 17, p. 154.

fertilizer experiments, and also founded an agricultural machinery factory (Fig. 1.5). His most important works appeared in 1837 (on soil science)[22] and 1839 (on fertilizer theory).[23]

These works remained largely unnoticed for a long time. Only in 1952 did the agricultural chemist and soil scientist Fritz Giesecke (1896–1958), most recently director of the Agricultural Testing and Research Institute in Braunschweig, acknowledge Spengler's achievements in a commemorative publication, after the dissertation of his student G. Wendt had already appeared in 1950, which dealt extensively with Carl Sprengel.[24]

Fig. 1.5 Portrait of Sprengel

[22] Sprengel, C.: *Die Bodenkunde oder die Lehre vom Boden, nebst einer vollständigen Anleitung der chemischen Analyse der Ackererden und den Resultaten von 170 chemisch untersuchten Bodenarten aus Deutschland, Belgien, England, Frankreich, der Schweiz, Ungarn, Rußland, Schweden, Ostindien, Westindien und Nordamerika—Ein Handbuch für Landwirthe, Forstmänner, Gärtner, Boniteure und Theilungscommissäre*, Leipzig 1837.

[23] Sprengel, C.: *Die Lehre vom Dünger oder Beschreibung aller bei der Landwirthschaft gebräuchlicher vegetabilischer, animalischer und mineralischer Düngematerialien, nebst Erklärung ihrer Wirkungsart*, Leipzig 1839.

[24] Wendt, G.: *Carl Sprengel und die von ihm geschaffene Mineraltheorie als Fundament der neuen Pflanzenernährungslehre*, Dissertation at the math.-nat. Sci. faculty, University of Göttingen (book publication) Wolfenbüttel 1950.

1.4 Liebig's Preliminary Research: From *Pure* to *Applied Chemistry*

Liebig's biographer Adolph Kohut (1848–1917) quoted Liebig himself on his transition to applied chemistry as follows: "After 16 years of the most strenuous effort, I assembled the results obtained insofar as they concerned plants and animals, into my chemistry applied to agriculture and physiology, two years later into my animal chemistry and the investigations made in other directions into my chemical letters. Not so much in the facts as in the descriptions of the organic processes were some mistakes made; but we were the first pioneers in unknown territory, and the obstacles to keeping on the right path were not always surmountable. Now that the paths of investigation are paved, it is a good part easier; but all the wonderful discoveries to which the recent era has given birth were then the stuff of our dreams whose realization we confidently and trustingly anticipated."[25] (*Adolph Kohut (1847–1917), Germano-Hungarian literary and cultural historian, biographer.)

By "paths of investigation" he meant elemental organic analysis developed by Liebig as well as nitrogen analysis by Liebig's students Heinrich Will (1812–1890) and Franz Varrentrapp (1815–1877) (see further down).

Almost half a century later, Richard Blunck (1895–1962; writer, publicist and biographer) formulated even more clearly Liebig's switch to applied chemistry, in his chapter on 'Revolution in Agriculture':

"By the end of the thirties, the process of organic analysis was so nearly complete and tested that its handling was no longer far removed from pure craftsmanship, and it became even more so when Will and Varrentrapp, Liebig's students, in 1841 developed a method for nitrogen determination that worked as reliably, quickly and simply as the five-bulb apparatus. This extinguished Liebig's interest in elemental analysis. The path was now well-trodden and accessible to many."[26]

1.4.1 Excursion into Elemental Analysis

In the combustion (oxidation) of organic substances with oxygen, water (vapor) forms (from the hydrogen) and carbon dioxide. The difficulties of an exact, quantitative analysis consist in, on the one hand, carrying out the combustion completely, and on the other hand, determining the mass (weight) of the water and the carbon dioxide separately. Copper oxide is used to produce oxygen, part of which is released when heated. The water is chemically bound in a tube filled with calcium chloride and established by weighing. To determine the carbon dioxide, Liebig developed a method to capture the gas in an aqueous solution (potash lye) instead of measuring the volume (with mercury) or by absorption on

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[25] Kohut*, A.—see note 3, pp. 109–110.

[26] Blunck, R.: J*ustus von Liebig. Die Lebensgeschichte eines Chemikers*, Hamburg 1946, pp. 131 ff.

solid potassium hydroxide. By designing his five-bulb apparatus, Liebig succeeded in separating the gases produced during combustion: They first flow through a tube filled with calcium chloride, where the water is absorbed. The remaining gases are directed into the vessel filled with potash lye (Fig. 1.6). W. Strube describes this apparatus very vividly in his Liebig biography and states: “The arrangement of the analysis substance in the horizontally lying combustion tube was Liebig’s borrowing from Berzelius, but he improved it by inserting the tube into a sheet metal pan furnished with movable segments. This allowed him to heat the reaction tube in separate zones, thereby accelerating or delaying

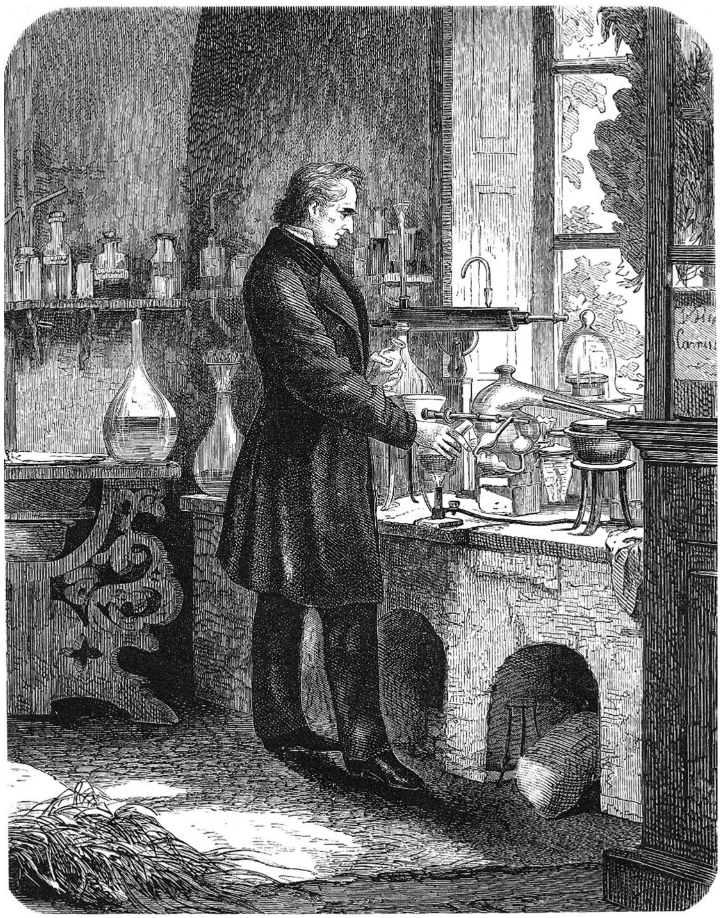

Fig. 1.6 Liebig in his laboratory with a five-bulb apparatus and combustion apparatus. (© Ann Ronan Picture Library/Photo 12/picture alliance)

the combustion process at will. The elemental analysis of organic compounds, hitherto a task for specialists, became routine."[27]

An addition to the elemental analysis to determine hydrogen and oxygen came with the method devised by his students for establishing nitrogen. This determination according to Will and Varrentrapp is based on the conversion of nitrogen from an organic substance into ammonia. The substance to be analyzed is heated in a combustion tube with a mixture of potassium hydroxide and calcium hydroxide. At red hot, ammonia forms from the nitrogen, which is collected in hydrochloric acid. The following quantitative analysis involved weighing the precipitation as ammonium platinum chloride. This method was in general use prior to the development of Kjeldahl's nitrogen determination in 1883.

R. Blunck continued, right after the excerpt quoted above:

"For Liebig, in 1840, pure, systematic organic chemistry was essentially finished. Now, in the shortest possible time, groups in the laboratory and elsewhere could gain insight into entire classes of bodies, and could hope to solve the mystery behind all organic substances, insofar as they present themselves outside the organism …"[28] Liebig's biographer Kohut wrote[29]: "The new direction of his work regarding the questions of plant and animal bodies was opened by *Justus Liebig's* epoch-making book mentioned above, in 1840: '(Organic) Chemistry and Its Applications to Agriculture and Physiology', which caused such an unusual stir that within six years, six editions of it were printed."

1.5 On the Substance of Liebig's Agricultural Chemistry

The first part of the book, designated as: The Chemical Processes in the Nutrition of Vegetables, contains the basics of plant nutrition or plant physiology. Liebig starts with analyses of the constituent elements of plants, then deals with the assimilation of carbon, hydrogen and nitrogen. In between, he describes the origin and action of humus, and he asserts:

"Humus does not nourish plants by being taken up and assimilated in its unaltered state, but by presenting a slow and lasting source of carbonic acid which is absorbed by the roots, and is the principal nutriment of young plants at a time which, being destitute of leaves, they are unable to extract food from the atmosphere."

The following statements are among the fundamental points of this chapter:

- "Physiologists reject the aid of chemistry in their inquiry into the secrets of vitality, although it alone can guide them in the true path; they reject chemistry, because in its pursuit of knowledge it destroys the subjects of its investigation; but they forget that the knife of the anatomist must dismember the body, and destroy its organs, if an account is to be given of their form, structure, and its functions."

[27] Strube, W.: *Justus Liebig. Eine Biographie*, Beuchta 1998, pp. 77–78.

[28] See note 26.

[29] See note 3, p. 121.

- “An experiment is the expression of a thought: we are near the truth when the phenomenon, elicited by the experiment, corresponds to the thought; while the opposite result shows that the question was falsely stated, and that the conception was erroneous.”
- Thus, Liebig assigns to chemistry an essential role also in research on plant nutrition. And in connection with the formation of humus, we read:
- “Whatever we regard as the cause of these transformations, whether the Vital Principle, Increase of Temperature, Light, Galvanism, or any other influence, the act of transformation is a purely chemical process. Combination and Decomposition can take place only when the elements are disposed to these changes. That which chemists name affinity indicates only the degree in which they possess this disposition.”
- The preliminary researches by other scientists, whom Liebig specifically names in these initial sections, play a significant role alongside the results of quantitative analysis. The chapter on: The Inorganic Constituents of Plants follows.

In the chapter: The Art of Culture, the processes of plant growth (again with numerous references to earlier authors) are considered as an overall process, before he then addresses the prevailing practice of his time in the chapter: The Interchange of Crops, and of Manure. One core statement by Liebig is:

“… that a soil must gradually lose those of its constituents which are removed in the seeds, roots, and leaves of the plants raised upon it. The fertility of a soil cannot remain unimpaired, unless we replace in it all those substances of which it has been thus deprived.

Now this is effected by *manure*.”

Following this section, Liebig appends in the German edition two contributions—by the forestry researcher Theodor *Hartig* (1805–1889; son of Ludwig Georg Hartig, see below) on plant nutrition (*Ueber Ernährung der Pflanzen*) [in Playfair’s English translation of 1840, it is in the section: Nutrition and Growth of Plants, in chapter: The Art of Culture, p. 124] and On the [Green] Manuring of the Soil in Vineyards (*Gründüngung in Weinbergen*, quoted from a letter by Administrator Krebs from Seeheim).

Hartig had studied forestry at the Forestry Academy and at the University in Berlin and taught from 1838 at the *Collegium Carolinum* in Braunschweig as a professor of forestry. At Riddagshausen he established an arboretum and began teaching woodland botany and general cultivation of forests.

The second part of Liebig’s work is titled The Chemical Processes of Fermentation, Decay and Putrefaction—processes that he, in accordance with the state of science of his time (before Louis Pasteur, born 1822), referred to as *chemical metamorphoses*. In addition to describing chemical processes, it features the action of yeasts (beer, wine) and *ferments*. That yeast contains microorganisms was later discovered in 1837 independently by three scientists (including T. Schwann, anatomist and physiologist), and Louis Pasteur demonstrated in 1862 that microorganisms are responsible for fermentation. Eilhard Mitscherlich first used the term ferment in the sense of enzyme (coined by the physiologist Wilhelm Friedrich Kühne (1837–1900) in 1878), i.e., a substance that is not transformed during a reaction, but is needed for a reaction to occur. Liebig also used the terms *contagions* and *miasmas.* Miasma was understood to be a disease-causing material which forms by putrefactive processes in air or water. The founder of the doctrine of miasmas is considered to be Hippocrates of Kos (around 460 to 375 BC). The physician Galen (Galenos of Pergamon, 130 to 210 AD) referred to a contagion as that which brings people into contact with disease-causing miasmas in the broadest sense.

1.6 Natural Scientists Mentioned by Liebig[30]

Liebig mentions numerous natural scientists who had treated topics pertinent to his book or had conducted preliminary research. He rarely gives a specific source, i.e., a publication. Some selected examples should serve to illustrate that he had indeed intensely studied the work of his predecessors.

In the chapter: Of the Assimilation of Carbon, he names—quoting the statement: "The leaves and other green parts of plants absorb carbonic acid, and emit an equal volume of oxygen"—among others, the observations by Priestley and Senebier as well as de Saussure. Joseph *Priestley* (1733–1804, British scientist) had been particularly occupied with the chemistry of gases. Nicolas Théodore de *Saussure* (1767–1846) was a Swiss natural scientist who became especially renowned as a botanist. The Genevan pastor Jean *Senebier* (1742–1809) studied the influence of sunlight on plants and plant respiration.

One of the few exact citations in the chapter on: The Assimilation of Carbon refers to the book by the physician and botanist Franz Julius *Meyen* (1804–1840), who on the recommendation of Alexander von Humboldt had participated in a circumnavigation of the world from 1830 to 1832 as a ship's doctor. Meyen published his *Neues System der Pflanzenphysiologie* in three volumes from 1837 to 1839. Elemental analysis plays a major role in Liebig's quantitative results. For example, he mentions analyses by his students Petersen and Friedrich Karl Ludwig *Schödler* (1813–1884) on the composition of 24 different types of wood.

In the chapter: On the Origin and Assimilation of Nitrogen, Liebig refers several times to the researches by the French chemist Jean Baptiste *Boussingault* (1802–1887), who was professor of chemistry in Lyon from 1832 and from 1845 professor of agriculture at the University in Paris, and of analytical chemistry at the *Conservatoire des Arts et Métiers* in Paris. He is considered one of the co-founders of agricultural chemistry for his significant research on nitrogen metabolism in plants.

In the chapter on: The Inorganic Constituents of Plants, the name Berthier often appears alongside de Saussure in the analyses of plant ashes. Pierre *Berthier* (1782–1861) was a French geologist and mineralogist. His works include studies on phosphate, which were of great importance for the development of fertilizer theory in agriculture.

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[30] Pötsch, WR, Fischer, A and Müller, W: *Lexikon bedeutender Chemiker*, Thun/Frankfurt (M.) 1989. Brock, WH: *Viewegs Geschichte der Chemie*, Braunschweig/Wiesbaden 1997.

Weyer, J: *Geschichte der Chemie,* Vol. 1 *Altertum, Mittelalter,* 16th–18th centuries and Vol 2, 19th and 20th centuries, Heidelberg/Berlin 2018.

In the chapter: The Art of Culture, Liebig also mentions the researches of two forestry scientists - Hartig and *Forstmeister* Heyer, as well as the agricultural scientist von Schwerz.

Georg Ludwig *Hartig* (1764–1837) had made his career in the state forestry service, by 1811 becoming Chief Forestry Master in the Prussian General Administration of Domains and Forests in Berlin. In 1821 he established a chair for forestry science at the University of Berlin, which later developed into the Forestry College in Eberswalde. He introduced the concept of sustainability in forestry in numerous publications as early as around 1800. In 1831 a "succinct" handbook for foresters, chamberlains and forest owners appeared under the title *Die Fortwirtschaft in ihrem ganzen Umfange in gedrängter Kürze.*

Johann Nepomuk Hubert von *Schwerz* (1759–1844) was an agronomist. At the behest of the King of Württemberg, he founded a state agricultural teaching institution in Hohenheim in 1818 from which the current University of Hohenheim emerged. This son of a Koblenz merchant had attended the Jesuit college in Koblenz and was then employed as a private tutor for the Count of Renesse, whose widow appointed him in 1801 as the manager of the count's estate farms in present-day Belgium. He acquired comprehensive expertise in agriculture from his own field trials, through the study of specialist literature and his educational travels. On the nomination of Albrecht Thaer, he first entered Prussian service as a government councilor in 1816, was inspector of agriculture in Westphalia and Rheno-Prussia and submitted proposals for its improvement, before he followed the call by King Wilhelm I of Württemberg to a chair. In Hohenheim he wrote his field guide cited by Liebig, *Anleitung zum practischen Ackerbau* (published by Cotta in three volumes 1823–1828; second ed. 1838, third ed. 1843, fourth ed. 1857).

The master of forestry Carl *Heyer* (1797–1856) was a practitioner. He was engaged in various positions in the Hessian forestry administration from 1817. He also taught at the Hessian Forestry School in Giessen and laid down the "golden rule" of tree thinning.

The Swiss botanist and natural scientist Augustin-Pyrame de *Candolle* (1778–1841) is mentioned several times by Liebig in the chapter on: The Interchange of Crops and Manure. After studying medicine and botany in Paris, de Candolle was appointed in 1808 to the chair for botany in Montpellier. In 1817 he founded the first botanical garden in Geneva and taught at the university (1834 chair for botany and zoology). Liebig wrote: "Of all the views which have been adopted regarding the cause of the favourable effects of the alternations of crops, that proposed by M. Decandolle alone deserves to be mentioned as resting on a firm basis." Another name Liebig mentioned was the Genevan botanist and chemist Macaire-Princep (1769–1869), whose numerous publications had to be identified. In addition to Macaire, Liebig also mentions Marcet; the two co-published chemical researches together; it is known that Alexander *Marcet* (1770–1822) was a doctor and chemist from Geneva, had worked in England and after his return home in 1819 received a professorship in medical chemistry. In his section on manure, Liebig cites their joint analyses of fresh "excrements of a cow."

In the appendix to the chapter on: The Interchange of Crops and Manure, Liebig added two different contributions: "Observations on a plant" by William *Magnab* (1780–1846), "Director of the Botanical Garden in Edinburgh" and Experiments and Observations on the Action of Charcoal from Wood on Vegetation by Eduard *Lucas* (1816–1882), a German pomologist. In 1841 he headed the botanical garden in Regensburg, was appointed in 1843 as the institute gardener to the newly founded horticultural school, the Agricultural Experimental and Teaching Institute in Hohenheim, and founded a private school for horticulture, fruit cultivation and pomology in Reutlingen in 1859/1860. One source of the section: On the Nutrition and Growth of Plants [in the English translation, subsumed under: The Art of Culture] is the aforementioned forestry expert Theodor Hartig.

In the second part: The Chemical Processes of Fermentation, Decay and Putrefaction, Liebig mentions numerous natural scientists, all of whom have played an important role in the history of chemistry—notably:

Berthollet (1748–1822), *Berzelius* (1779–1848), *Bunsen* (1811–1899), *Döbereiner* (1780–1849), *Dumas* (1800–1884), *Gay-Lussac* (1778–1850), *Geiger* (1785–1836), *Regnault* (1810–1878), *Thénard* (1777–1857), *Wöhler* (1800–1882). Lesser known names include: Gerardus Johannes *Mulder* (1802–1880), from 1840 professor in Utrecht with important investigations in the field of physiological chemistry and agrochemistry; Karl Gustav *Bischof* (1792–1870), professor in Bonn, pioneer of mineral water analytics, and Frédéric *Kuhlmann* (1803–1881), professor of applied chemistry in Lille.

This list of scientists mentioned variously by Liebig also makes his book become a part of the history of chemistry, especially from the period around 1800.

1.7 On the Dissemination of Liebig's Work

About the dissemination of Liebig's book, his bibliographer Carlo Paoloni reported, among other things, that in 1840 Liebig also addressed a wider audience for the first time and, despite his aversion to authorship, decided to "set down in writing the implementation of all his knowledge in organic chemistry toward the elucidation of life's processes in plants and animals."[31]

A letter from April second to his friend Wöhler in Göttingen informs us:

"You know, I am currently writing an insane chemistry that deals with physiology and agriculture. How stunned people will be to think that a chemist would dare to claim that physiology and agronomy are the most ignorant bunglers … ".[32]

The aforementioned work first appeared with the assistance of his student Charles Frédéric Gerhardt (1816–1856, from Strasbourg, in Giessen 1836/37, from 1838 assistant to Dumas) on April 10, 1840 with a dedication by Gay-Lussac in French, under the title *Traité de Chimie Organique* (Paris 1840): "This book contains for the first time as an *introduction,* on 195 specially numbered pages, Liebig's agricultural chemistry, under the

[31] Paoloni, C.: J*ustus von Liebig. Eine Bibliographie sämtlicher Veröffentlichungen,* Heidelberg 1968.

[32] Quoted from: Paoloni, C.: Das Entstehen und die Entwicklung der Agrikulturchemie Liebigs im Lichte der Bibliographie (1840–1873), in: *Berichte der Justus-Liebig-Gesellschaft zu Giessen*, Vol. 1, *Symposium 150 Jahre Agrikulturchemie*, Giessen 1990, pp. 7–18.

title ‘Application des principes de Chimie Organique à la Physiologie végétale et animale’. This publication evidences the priority of the French edition of Liebig’s agricultural chemistry over the first German edition on August 1, 1840.”[33] In 1841, the French translation by Charles Gerhardt of the first German edition was published with the following preface by Liebig, in which he states[34]:

“I have already presented this work as an *introduction* to my ‘Traité de Chimie Organique’, but since the subject matter it deals with is outside of true chemistry, it seemed appropriate to me to present it separately in the field of physiologists and agronomists …”.

Liebig was obviously certain of the success of his work, as can be inferred from letters to his publisher and friend Eduard Vieweg (1797–1869).[35] A letter dated March 17, 1840, reads, among other things: “It will … cause a great stir. I have developed a theory of plant nutrition, the influence of humus and fertilizer and a theory of wine and beer production based on experiments and observations, which could bring about a revolution in prevailing views …”.

And in another letter dated April 16, 1840, Liebig asked for a print run of 1500 copies and wrote: “Don’t worry, you shall sell them, the book will be bought by chemists, pharmacists, doctors and economists, that is a large audience …”.

The first German-language edition was published on August first with a dedication to Alexander von Humboldt. One of the most important statements is found on page 144/145 [here in English trans. (1840), p. 161] also quoted by Paoloni:

“But agriculture has hitherto never sought aid from chemical principles, based on the knowledge of those substances which plants extract from the soil on which they grow, and of those restored to the soil by means of manure. The discovery of such principles will be the task of a future generation, for what can be expected from the present, which recoils with seeming distrust and aversion from all the means of assistance offered it by chemistry, and which does not understand the art of making a rational application of chemical discoveries? A future generation, however, will derive incalculable advantage from these means of help.”

In Germany, a total of ten editions were published between 1840 and 1877, in America 19 editions between 1841 and 1872, and in England five editions between 1840 and 1847. Paoloni identified further editions or translations in France (1841, 1844), Italy (1842, 1844), Holland (1842), Belgium (1850), Russia (1842), Denmark (1846), Sweden (1846) and Poland (1846).[36,37]

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[33] See note 32.

[34] In translation. See note 32.

[35] See note 32.

[36] See note 31.

[37] See note 32.

1.8 Critical Voices—Reviews and Further Developments to the Present Day

In the first years after the publication of Liebig's *Agrikulturchemie*, some critics voiced their opinions, understandably focusing on the lack of field experiments in it.

In a detailed book review in the *Jahrbuch für wissenschaftliche Kritik* in 1843, a journal which dates back to Lavoisier, we read among other things, with reference to Liebig's book:

"It has undergone various evaluations, laudatory and sharply critical ones. In the latter, Liebig is perhaps himself partly to blame, as he sought to chastise with overly caustic polemics many a supposed aberration which, according to him, scientists have fallen for in the study of natural science. The correctness of many facts and views he has put forward has been challenged as well. Liebig is nevertheless far from properly advocating everything he has developed, and may partly reject; but novel, smart views and hypotheses, even if they not be confirmed, are, in every science, conducive and beneficial; they attract attention and engage more astute minds, the more inspirational they are, they provoke contradiction and experiments and thereby advance science."[38]

Paoloni[39] also mentions the names of the most important critics: Hlubeck, Gruber, Schleiden, Sprengel and Mohl came forward to oppose Liebig's principles.

Franz Xaver von *Hlubek* (1802–1880) was an Austrian agronomist, from 1830 professor of agriculture and forestry in Vienna, from 1840 at the Johanneum in Graz (now a *Technische Universität*) as well as agricultural writer. He is considered one of the pioneers of agronomy. *Gruber* is described as an interpreter of the views of *Sprengel* (see there). Matthias Jacob *Schleiden* (1804–1881) was a botanist, from 1839 Extraordinarius in Jena (from 1850 Ordinarius), and co-founder of the cell theory, who held lectures for educated citizens after the model of Alexander von Humboldt. Hugo von *Mohl* (1805–1872) was a physician and botanist, became professor of physiology in Bern 1835 and in the same year was appointed Ordinarius for botany at the University of Tübingen. Paoloni also reported that Liebig's friend Berzelius had written a "nasty comment" on Liebig's book in a letter dated December 11, 1840.

These criticisms did not tarnish the success of Liebig's work, however. Further critique, especially with regard to Liebig's mineral theory, came from John Bennet Lawes (1814–1900, owner of a farm in Rothamsted, Hertfordshire County, nowadays the largest agricultural research institute in England) and from Gilbert from England. Lawes conducted experiments with fertilizers and particularly challenged the thesis that ammonium salts from the soil supplied nitrogen. Joseph Henry Gilbert (1817–1901) had been a student of Liebig's in Giessen in 1840 and opened a superphosphate factory together with Lawes in 1843. The patented fertilizer developed by Liebig had not proven itself due to the

[38] *Jahrbuch für wissenschaftliche Kritik* (1843) Vol. 1 (February), col. 262—the author: Carl Heinrich Schultz (1804–1876), physician and botanist.

[39] See note 32.

poor solubility of some of the ingredients. Liebig was also involved in a bitter priority dispute in France—for more details see W. H. Brock.[40]

New findings prompted Liebig to publish more—for instance his *Principles of Agricultural Chemistry, with Special Reference to the Late Researches Made in England*, which originally appeared in German in 1855.[41]

In 1862, the "epoch-making standard work of Liebig's Agricultural Chemistry" (Paoloni) appeared in two parts and two volumes under the titles *Der chemische Process der Ernährung der Vegetabilien* and *Die Naturgesetze des Feldbaues*.[42]

The first part includes, among other things, the analytical results of 709 plant ashes as well as of excrement, stable manure, sheep dung, manure slurry, guano, bone, and peat.

The following main theses are presented in his work published in 1840:

- "As a principle of agriculture, it must be assumed that soil must fully regain what is taken from it. The form in which this restitution occurs, whether in the form of excrements or ash or bones, is quite inconsequential.
- The yield of a field is limited by the nutrient that is at a minimum against the needs of the plants. (This finding later became known as the *law of the minimum*.)
- We can maintain the fertility of our fields in a constantly stable state if we replace their loss annually, an increase in fertility, an increase in their yield is only possible if we give back more than we take from them.
- The source from which nitrogen continuously flows to soil and a plant is the atmosphere." (Liebig later corrected this thesis.)[43]

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[40] Brock, WH: *Justus von Liebig. Eine Biographie des großen Wissenschaftlers und Europäers*, chap. 6 on Liebig and farmers, pp. 121–149, Braunschweig/Heidelberg 1999.

[41] *Die Grundsätze der Agricultur-Chemie, mit Rücksicht auf die in England angestellten Versuche*, first ed. and 2nd "edition expanded by an addendum", Braunschweig 1855; English and American editions entitled *Principles of Agricultural Chemistry, with Special Reference to the Late Researches Made in England* and *The Relation of Chemistry to Agriculture and the Agricultural Experiments of Mr. J. B. Lawes*, translated by Samuel W. Johnson at the author's request."

[42] Paoloni, C.: *Justus von Liebig. Eine Bibliographie sämtlicher Veröffentlichungen*, Heidelberg 1968, pp. 184 and 185.

[43] Schulz, St., Menzel P.: J*ustus von Liebig "Alles ist Chemie"*. Exhibition at the University of Hohenheim March 5–April 30, 1999, accompanying documentation, University of Hohenheim 1999.

Graphic representations of Liebig's agricultural chemistry can also be found in his *Chemische Briefe* from the 33rd letter (on "principles of rational agriculture …") to the 48th/49th letter (on "The standpoint of modern agriculture to history …" or "Agriculture in China"); sixth edition. Leipzig and Heidelberg 1878 (= reprint of the last edition under the author's supervision).

1.8.1 Liebig's 50 Theses

The "epoch-making 50 theses, which he later published as axioms of his doctrine and which have only changed with regard to the solubility of plant nutrients by incorporating the law of soil absorption", are also listed by his biographer Kohut. They read as follows[44]:

1. "Plants generally receive their carbon and nitrogen from the atmosphere, carbon in the form of carbonic acid, nitrogen in the form of ammonia. Water (and ammonia) supplies plants with their hydrogen; the sulfur of sulfurous components of plants comes from sulfuric acid.
2. On the most diverse types of soil, in the most diverse climates, whether grown on the plain or on high mountains, plants contain a certain number of mineral substances, always those manifested by the nature and properties of the constituents of their ashes. These ash constituents were components of the soil; all fertile soil types contain certain amounts of them; in no soil in which plants thrive are they absent.
3. In the produce from the field, the entire quantity of soil components, which became constituents of the plants, is extracted and removed from the soil at harvest; prior to sowing, the soil is richer in these than after the harvest, the composition of the soil is changed after harvesting.
4. After a series of years and a corresponding number of harvests, the fertility of the fields diminishes. With all other conditions remaining the same, the soil alone has not remained what it was before; the change in its composition is the probable cause of its becoming infertile.
5. The lost fertility is restored by fertilizer, manure, excrements of humans and animals.
6. Fertilizer consists of decaying plant and animal substances, which contain a certain amount of soil components. The excrements of animals and humans represent the ash of the food metabolized in the bodies of animals and humans from plants that had been harvested in the fields. Urine contains the water-soluble soil components, the feces the insoluble soil components of the nutrients. Fertilizer contains the soil components of the harvested products off the field; it is clear that by its incorporation into the soil, the soil regains the extracted mineral components; a restoration of its original composition is accompanied by a restoration of its fertility; it is certain that one of the conditions of fertility was the soil's content of specific mineral components. Rich soil contains more of them than poor soil.
7. The roots of plants behave in relation to the absorption of atmospheric nutrients similarly to leaves, i.e., they likewise possess the ability to absorb carbonic acid and ammonia and use them in their organism in the same way that the absorption through the leaves would have done.
8. Ammonia, which the soil contains and which is added to it, behaves like a soil component, carbonic acid behaves in the same way.

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[44] Kohut, A.—see note 3, quote on pp. 111–121.

9. Plant and animal substances and animal excrements, decay and mold. The nitrogen of the nitrogen-containing components of the same is transformed into ammonia as a consequence of decay and molding; a small part of the ammonia is transformed into nitric acid, which is the product of the oxidation (the decay) of ammonia.
10. We have every reason to believe that in the nutritional process of plants, nitric acid can substitute ammonia, i.e., its nitrogen can be used for the same purposes in their organism as from ammonia.
11. Accordingly, animal manure not only provides plants with the mineral substances which the soil must supply, but also the nutrients which the plant draws from the atmosphere. This provision is an increase in the quantity contained in air.
12. The non-gaseous nutrients, which the soil contains, enter the organism of plants through the roots. Their transition is mediated by water, by which they become soluble and mobile. Some dissolve in pure water, others only in water which contains carbonic acid or an ammonia salt.
13. All those materials which make the insoluble soil components in water soluble, when contained in the soil cause the same volume of rainwater to absorb a larger amount of them.
14. Through the progressive decay of plant and animal remains contained in animal manure, carbonic acid and ammonium salts form. They represent a source of carbonic acid active in the soil, which causes air in the soil and the available water in it to become richer in carbonic acid than without their presence.
15. Animal fertilizers not only offer plants a certain sum of mineral and atmospheric nutrients, but they also receive from the same, with carbonic acid formed by its decay, an indispensable means to tranform in a larger quantity the components insoluble in water within the given time, thus without the participation of the usable organic substances.
16. In warm dry years, plants receive less water through the soil than in wet years. The harvest in different years is proportional to this. A field with the same properties produces a lower yield in years with little rain; it increases in rainier years, with the same average temperature, up to a certain limit for the amount of rain.
17. Of two fields, one of which contains more nutrients in total than the other, the richer one also yields a higher yield in dry years, under otherwise equal conditions, than the poorer one.
18. Of two fields with the same properties and the same content of soil components, one of which also contains a source of carbonic acid in decomposable plant or fertilizer constituents, the latter produces a higher yield in dry years than the other. The cause of this difference or inequality in yield is based on the unequal supply of soil components in quantity and quality, which the plant receives from the soil during the same times.
19. All obstacles hindering the solubility and absorbability of the nutrients present in the soil for plants, restrict to the same degree their ability to serve as nutrition, i.e. they render the food ineffective. A certain physical condition of the soil is a necessary

precondition for the effectiveness of the nutrients contained therein. The soil must allow atmospheric air and water access, and the root fibers the possibility to spread in all directions and to seek out the nutrients. The term 'telluric conditions' denotes the sum of all conditions necessary for the development of plants, dependent on the physical properties and composition of the soil.

20. All plants without exception require phosphoric acid, sulfuric acid, alkalis, lime, bitter earth, and iron for their nutrition; certain plant genera need siliceous earth; plants growing on the seashore and in the sea need common salt, soda, iodine metals. In several plant genera, the alkalis can be partially substituted by lime and bitter earth and these in turn by alkalis. All these substances are subsumed in the term mineral nutrients; atmospheric nutrients are carbonic acid and ammonia. Water serves as a nutrient and mediates the nutritive process.
21. The nutrients necessary for a plant are of equal value, i.e., if one of the total number is missing, the plant does not thrive.
22. Fields suitable for the cultivation of all plant species contain all the components necessary for the plant species; the words fertile or rich, infertile or poor express the relative relationship among these soil components in quantity or quality. Under qualitative difference, one understands the unequal state of solubility or ability to transfer the mineral nutrients into the plant organism, which is mediated by water. Of two types of soil, which contain equal amounts of mineral nutrients, one can be fertile (viewed as rich), the other infertile (viewed as poor), if in the latter these components are not free but are bound in a chemical compound. A body that is in a chemical compound, due to the attraction of its other components, offers a resistance to a second one that strives to combine with it, which resistance must be overcome if both are to combine.
23. All types of soil suitable for cultivation contain the mineral nutrients of plants in these two states. All together represent the capital, the freely soluble ones represent the fluid, mobile part of the capital.
24. To improve, enrich, and make a soil fertile by suitable means, but without the addition of mineral nutrients, means to liberate a part of the dead, immobile capital, that is to make the chemically bound components free, mobile and usable for plants.
25. The mechanical tillage of a field aims to overcome the chemical resistances in the soil, to liberate the mineral nutrients bound in a chemical compound and make them usable. This is done by means of the atmosphere, carbonic acid, oxygen, and water. The action is called weathering. Standing water in the soil, which prevents the atmosphere from accessing the chemical compounds, is resistance to weathering.
26. Fallow time means the time of weathering. During fallow, carbonic acid and ammonia are supplied to the soil by air and rainwater. The latter remains in the soil when substances are present that bind it, i.e., take away its volatility.
27. A soil is fertile for a given plant species when it contains the necessary mineral nutrients for this plant in a sufficient quantity, in the correct ratio, and in a condition suitable for uptake.