ENGINEERING ASPECTS OF FOOD PROCESSING

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Keywords: Metabolic energy requirement, food production, wet cleaning, dry cleaning, homogenization, membrane filtration, cyclones, clarifixator, coating, extrusion, agglomeration, fluidization, battering, uperisation, pasteurization, sterilization, baking, chilling, freezing, hydrocooling, cryoconcentration, glazing, extrusion-cooking, roasting, frying, thermoplasticity, logistics.

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Summary

The main aim of this chapter is to show the impact of chemical and process engineering on the development of nowadays food industry. The contribution presents food as a substance needed to keep a man alive, which is consumed every day and must be produced in enormous amounts. Food industry is a manufacturer of food, employs hundred of thousands of employees and uses considerable quantities of energy and water. Basic processes used in food processing are briefly described. They are divided into three groups of unit operations that are mechanical processes and heat and mass transfer processes. In each group of unit operations specificity of the process is emphasized. At the same time, it is shown how theories of momentum, heat and mass transfer developed by chemical engineering are applied in designing food-processing equipment. The question of hygienic design and processing of safe food is explicitly stressed. The role of food engineering as a discipline accounting for specificity in design of food processing equipment and its exploitation and assisting chemical engineering is shown. Some additional sources of information are recommended for those readers who would like to expand their knowledge on engineering aspects of food processing and production.

1. Introduction

Food is any substance that can be eaten or drunk by a man to keep him alive, nourished the body and give the pleasure. Food usually contains carbohydrates, proteins and fats as main constituents. Vitamins, minerals and hundreds other organic and inorganic compounds are important components of food responsible for nourishment, growth and well-being of man.
Food composition depends on its origin and the way of processing. Food is mainly sourced from plants and animals, but some inorganic compounds such as water and salt are important items of human diet.

Food is a source of energy and components for growth and repair of injuries. It is estimated that some 10^9 cells/min. are under constant repair and replacement in a human body. The requirement for energy and nutrients depends on the age and physical activity of a person. Energy derived from food is used for biochemical reactions (chemical energy), for body movement (mechanical energy), and to maintain the body temperature (thermal energy). The energy efficiency of the human body is about 60%, but half of it accounts for thermal energy. The basal metabolic energy requirement ranges from 5 to 7.5 MJ/day depending on age, sex, body mass and size. Requirement for nutrients is recommended by WHO and local authorities. Recommended Daily Allowance (RDA) is the level of different nutrients that assure maintenance, growth and repair of the body for 97.5% of the population.

Daily energy consumption depends on availability of food, eating habits, cultural and religious restrictions and health consciousness. It varies from less than 8 MJ/day in areas with shortage of food to over 15 MJ/day in developed countries. Some examples are presented in Table 1.

Country	MJ/day/person	Country	MJ/day/person
Somalia	7.30	New Zealand	13.54
Haiti	7.68	Mexico	13.67
Zambia	7.90	Spain	13.94
Chad	8.29	Turkey	13.98
Bangladesh	9.35	Poland	14.13
Argentina	9.66	Denmark	14.20
India	9.87	Switzerland	14.24
Japan	11.53	Hungary	14.32
Slovakia	11.83	United Kingdom	14.34
South Africa	12.14	Germany	14.62
China	12.31	Austria	15.29
Australia	12.80	Ireland	15.43
Saudi Arabia	12.80	Belgium	15.48
Russian Federation	12.98	Luxemburg	15.82
Sweden	13.06	United States of America	16.02
Finland	13.38	**World**	**11.59**

FAO Statistical Yearbook 2009. Average for the years 2003-2005.

Table 1. Food energy consumption in selected countries

The food energy is supplied by main food constituents. The energy value of proteins and carbohydrates is 16.74 kJ/g and for fats, it is 33.49 kJ/g. Hence, substantial amounts of those constituents must be consumed every day to provide body with sufficient energy. Taking into account that most foods contain large quantities of water and energetic efficiency of the body is 60% it shows how large mass of food is consumed per day by a statistical man. Consumption of some foods is presented in Table 2. The data in Table 2 shows just the consumption of basic foods, which for example for Poland sums up to 711.2 kg/year. Adding other commodities such as confectionery, beverages, wine, beer and luxury products, the mass of one tone or even more is obtained. It shows how huge amounts of food must be supplied every day.

Country	**Meat**	**Poultry**	**Fish**	**Milk**	**Eggs**	**Butter**	**Potato**	**Vegetables**	**Fruits**	**Grain**
Austria	95.1	16.9	14.7	299.8	12.9	5.2	59.7	90.4	137.2	110.8
Denmark	93.5	18.4	24.3	239.3	17.5	1.7	76.5	102.2	146.5	139.5
Finland	52.9	15.1	32.6	356.2	8.4	4.0	71.8	70.7	91.9	106.6
France	73.6	24.7	31.2	274.6	15.3	8.1	64.8	142.9	95.5	117.2
Germany	70.9	13.8	14.9	255.6	12.0	6.8	72.1	90.5	113.2	112.9
Hungary	59.1	30.2	5.1	168.9	16.5	1.0	69.1	117.0	137.2	125.4
Poland	56.9	19.1	13.1	173.4	11.6	4.5	130.1	100.3	47.6	154.6
Spain	91.6	30.4	47.4	173.8	13.1	0.8	78.6	143.3	112.7	98.9
Sweden	64.3	12.6	33.6	377.8	10.5	3.6	54.1	78.4	115.2	103.5

Food Balance Sheets, FAO 2006. Przemysl Spozywczy, 2008, 61(8), 26-31,75.

Table 2. Consumption of food in kg/person in 2003

2. Food Industry

Food is produced by the food industry. This industry is much diversified. There are small family run businesses almost like a craftsmen workshop, and large processing plants employing hundreds of workers. The size of the plant depends primarily on the kind of processed products, the market and expectations of consumers. Small enterprises produce specialty goods or regional products on local market as well as products of every day use and expected by consumers as freshly made. The example is production of bread, rolls and cakes, pasteurized fluid milk. Large processing plants produce basic commodities such as flour, culinary and processed meat, fruit juices, UHT milk, milk powder, fats, confectionary and frozen foods.

Food industry as a whole is a large part of national economy. It employs large number of people with different skills and education. In Poland, food industry employed in 2007 some 475 thousand people, which amounts to 1.25% of the population or 3.45% of total employment. In Germany, food industry in 2005 employed 845 thousand people, and the food industry of the European Union (EU-27) employed some 4.69 million people. Processing of food consumes huge amounts of energy and water. In Poland in 2007 total energy consumption by the food industry amounted to $8.82 \cdot 10^{16}$ J and water consumption was some $1.014 \cdot 10^{7}$ m^3. Total energy consumption referred to population of Poland yields some 6.36 MJ/day/person. It means that to supply a man with appropriate food energy, food industry must input more than 45% of that value in the form of heat and electrical energy.

Most food originating from plant and animal sources is perishable. It undergoes senescence, biological, microbiological, chemical and physical decay. Hence, food must be preserved in order to prevent loses. In temperate climate, agriculture is seasonal; therefore, preservation techniques are needed in order to allow food to be available out of the season. In developed countries more than 70% of the population live in metropolis and big cities, while production of raw materials for food is spread all over the country. Because of that, transportation of agricultural products and food becomes an important issue.

The basic aims of food industry today are as follows:

1. To preserve food and extend the time during which a food remains wholesome, can be distributed and stored, also at home.
2. To increase variety of products, which fulfill consumer expectations as far as price, diet, habits and other likes are concerned.
3. To manufacture convenience products in order to reduce the time required for meal preparation.
4. To provide products with appropriate nutritional quality.
5. To generate income for the company.

All the above-enumerated goals of the food industry are subordinated to the most important requirement - the safety of food. Hence, all the applied preservation techniques must assure safety of food in first place. That prerequisite enforces special design of processing equipment and facilities as well as management solutions.

3. Food Processing

Food processing involves combination of procedures and processes intended to change the raw materials into foodstuffs. The procedures and processes are conveniently called unit operations. The idea of unit operations allow unified description of production of different varieties of food.

From the processing point of view, raw materials can be classified as liquids and solids. Processing of liquids differs substantially from processing of solids, because it can be done in a hermetic system avoiding contact with surroundings. Hence, high standard of hygiene can be easily assured. Processing of solids is more complicated, and only partly can be isolated from the contact with surroundings. Hygienic solutions are more complex. Some solids are a source of liquids as semi-products, and some liquids are processed to solids. Therefore, food processing partly as liquids and partly as solids is a common practice.

Basic unit operations used in food processing are presented on Figure 1. All the unit operations applied in food processing can be divided into three main groups.

Mechanical processes include such unit operations as cleaning, size reduction, sorting, grading and removing of inedible parts, mixing and mechanical separation. Heating and cooling, evaporation, freezing all belongs to heat transfer processes. Mass transfer occurs in such processes as drying, extraction, crystallization and distillation. Nowadays ionizing radiation and electrical current are used to process foods. Moreover, in food processing there are also processes of complex nature, which cannot be assigned to any of the above groups. These are fermentation and some post-processing operations.

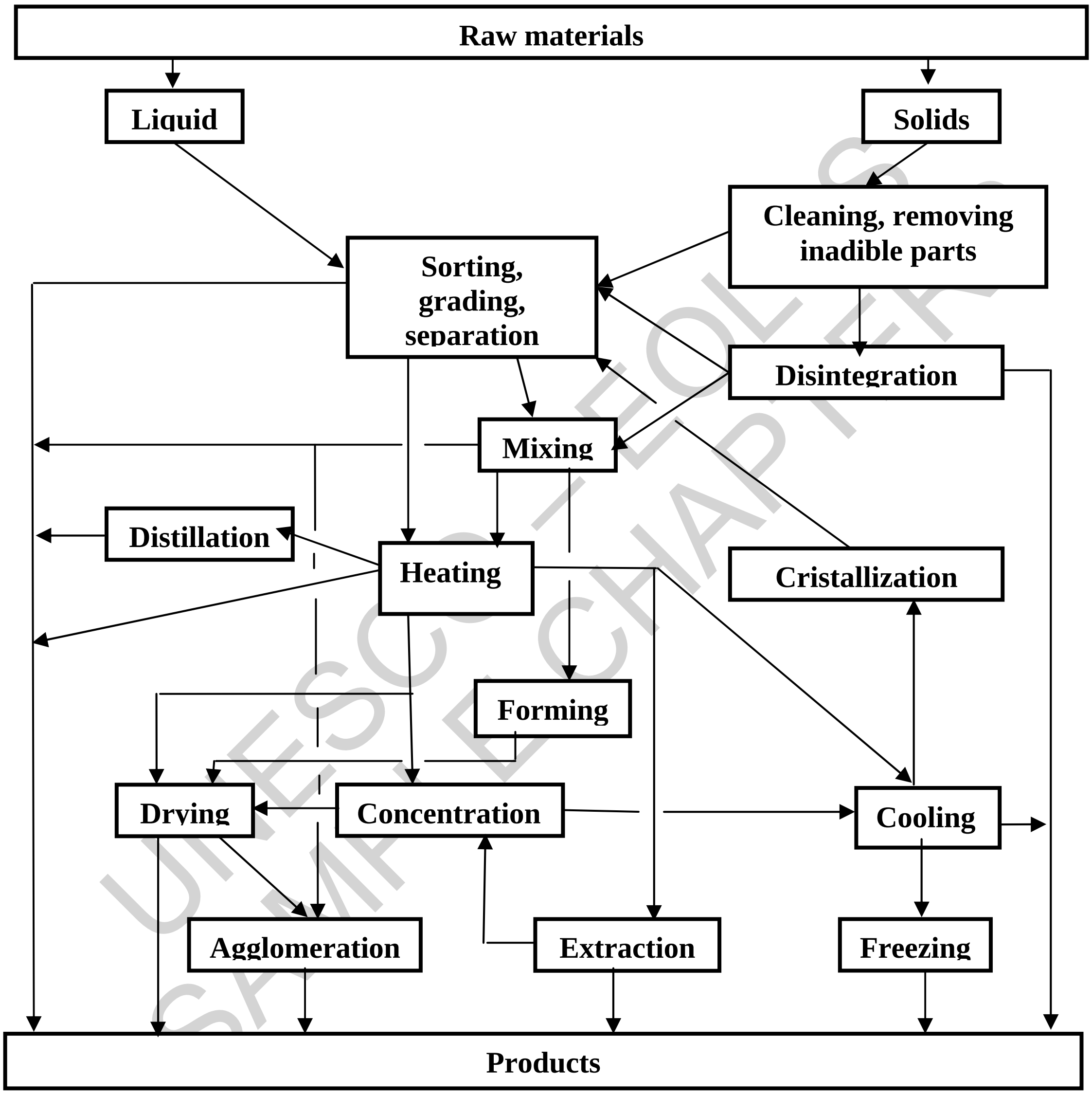

Figure 1. Basic unit operations in food processing

Many unit operations applied in food processing are well understood and theoretically described thanks to the knowledge brought about by chemical and process engineering. Application of momentum, heat and mass transfer theories in the design of food processing equipment is wide and very successful. However, there are still many processes, which are not fully understood or so complex, that their mathematical description would not be useful in the design or exploitation of equipment. These problems arise mostly from the structure and properties of processed material and their dependence on weather, agricultural practices and post-harvest treatment and processing.

3.1. Mechanical Processes

3.1.1. Cleaning of Raw Material

Mechanical processes are intended mostly to change physical properties of raw material and to prepare it to further processing. One of the first unit operations is cleaning, which is done in a wet or dry way. The way the raw material is cleaned depends on its nature, the type of soil to be removed, and further processing. In wet cleaning mechanical and hydrodynamic forces are used, and water serves as a cleaning agent. Cleaning soft materials easily damaged by mechanical forces, water is sprayed onto material surface or air is pumped into water, and vigorous mixing is caused. For wet cleaning such methods as soaking, brushing, spraying, air bubbling and flotation are used. For each of these methods equipment is designed mostly based on experience and observations.

Dry cleaning is less efficient than the wet one, but it is used for materials with low water content. Dry cleaning is applied for example to grains, nuts, and cocoa beans. Air is the cleaning agent, and differences in buoyancy are used to separate material from the contaminants. Cleaned material is fed into a stream of air and is usually separated into three fractions. Heavy debris fall first, then cleaned material and the light contaminants like stalks, husks are deposited as the last. The theory of flow of diluted mixture of particulates in gas, as well as sedimentation principles are used to calculate the air velocity. Aspiration cleaning is well designed and widely used in harvesting machines and grain storage and processing facilities.

3.1.2. Removal of Inedible Parts

Removal of inedible parts from the raw material is another important operation in food processing, which needs specially designed equipment. Mostly it is a mechanical operation but some chemicals and heat are also used. Destoning of fruits, deboning of meat and poultry, deheading of fish are the examples of mechanical operations, in which force is used to push out or to cut out an inedible part of the material. Derinders are very specialized machines used to deskin slaughtered animals. Mechanical force is used to separate the skin from meat, but the deskining must be initiated manually. Defeathering of poultry and dehairing of carcasses is done mechanically but is preceded by scalding (heat treatment). Evisceration of poultry and slaughtered animals is done manually, while gutting of fish is done either manually or mechanically. Peeling of fruits and vegetables is done by abrasion or using heat. Treatment with steam, hot solution of caustic soda or flame is practiced in food processing. From the above description, it is evident that the equipment used to remove inedible parts of the material is very specialized, designed just for the particular material taking into account its size and shape, physical properties and the job, which must be done. Only peeling equipment is more versatile. Hence, mechanically resistant vegetables such as potato, carrot, red beetroot can be peeled in abrasive machines, while soft materials as tomato, peaches, apricots are peeled be surface heating and removing scalded peel with water spray.

3.1.3. Disintegration

Disintegration of the material is a common process in food industry. It is done in order:

1. To fulfill expectations of the consumer,
2. To facilitate further processing,
3. To enable separation of parts of the material with different properties
4. To enable joining of different materials or parts of the material with special properties.

Food raw materials mostly contain large quantities of water; hence they properties differ very much from the properties of brittle materials. Theories of Kick, Rittinger or Wang are not applicable, except of some special cases like lime stone disintegration in sugar processing. Most of the disintegration equipment used in food processing is designed based on experience and observations.

Appropriate design of the disintegration equipment is very important because in many size reduction processes some precautions must be undertaken. For example, disintegration of potatoes for starch production or grain for flour must be done in such a way that the starch granules are not damaged. Disintegration of apple must assure free flowing of juice in pores of crushed apple bed during juice expression.

In size reducing machines compression, impact and shearing forces are mostly applied. Disintegrating machines use all three forces, but often one prevails over the others. Disintegrators are often equipped with screens hence; material only with appropriate size can leave the machine. Machines of that type reduce the size of the material but do not create any shape. Specialized machines are used for cutting, slicing and dicing.

Food materials are mostly visco-elastic, some show plasticity, and only some dry products can be treated as brittle. Because of that, use of energy for size reduction is small. Most of energy is used to overcome inertia and friction forces in disintegrating machines. Milling of wheat requires about 1 kJ/kg, chopping fresh meat, depending on the size, needs from 1 to 20 kJ/kg, and chopping of frozen meat needs 35 or 70 kJ/kg when pieces are 3 or 2 mm, respectively. Slicing of sugar beet requires energy from 0.9 to1.6 kJ/m^2, and for potatoes, the needed energy is about 0.6-0.7 kJ/m^2. The output of the disintegrating machines depends on the kind of disintegrated material, the degree of disintegration and further processing steps. It varies from hundreds of kilograms per hour to some 60 t/h.

In processing of liquid food, disintegration is also applied. The disintegration is applied to emulsions and suspensions of solids in liquids. Milk is an emulsion with variable size of fat globules and undergoes separation (creaming) under gravity. Some fruit juices contain fruit flesh, which sediments at the bottom of the bottle. Both, milk with the layer of cream on the surface or the juice with layer of sediment are not attractive to the consumer. The smaller is the size of fat drops or the pieces of fruit flesh the longer is the time of creaming or sedimentation. Disintegration of that type of products is done in homogenizers or colloidal mills. In homogenizers, shearing and cavitations are main causes of fat globules disintegration. The emulsion is forced through the narrow slit with high velocity. Pressure applied on the homogenizing valve is 40-60 MPa. Application of pressures exceeding 100-150 MPa leads to disintegration of microbial cells, and homogenization adds some pasteurization effect. In colloidal mills, suspension is forced into clearance between stationary and rotating disc, which rotates at 3000-15000 rev/min. Shearing forces cut pieces of suspension and retards sedimentation. Colloid mills are also used in production of paste-like products (peanut butter, meat paste).

Disintegration of the stream of liquid into small droplets is applied in spray drying. Formation of liquid droplets suspended in a gas is done in a centrifugal atomizer or in a pressure nozzle. The way the cloud of liquid droplets is formed depends primarily on the kind of sprayed material and the output of the dryer. Milk is mostly sprayed by centrifugal atomizers, while tea or coffee extracts are sprayed with nozzles. The important property of the spraying equipment is the size distribution of droplets. The narrow is the size distribution of droplets the efficient is the drying, and better is the quality of the dried product.

In food processing stream of gas is also divided into bubbles suspended in liquid in order to produce sparkling soft beverages, foamed products or to cause and facilitate mixing. For mixing purposes barbotage is used, while in foamed products processing vigorous mixing is applied.

3.1.4. Sorting and Grading

Some raw materials and disintegrated material often needs sorting. Sorting is done by weight, size, shape, and color. The need for sorting arises from few reasons.

1. Sorted material is much better appreciated by consumers. It is recognized as of good quality and subjected to appropriate technology.
2. Uniform weight, size or shape makes easier further processing and its control. Moreover, uniformity of quality of the final product is related to the size or weight of the material, especially in processes in which heat or mass transfer occurs.
3. Sorted material gives better control of filling and packing operations.
4. In some cases, size or weight of the material is related to its quality. For example, small green peas contain less starch and are sweeter than the large one.

Sorting is done mostly taking advantage of gravity force. Screens with fixed or variable aperture as flat or drum machines are commonly used. In the case of flat screens, vibration is applied to move the material, while in the drum design inclination and rotation cause movement of the material from inlet to outlet. Large objects are sorted in cable, rope, belt or roller sorters. In these machines, the material moves in between two cables, belts or rolls. The aperture between them increases continuously and material with prescribed size is collected along the sorter. Sorting may damage the material, especially that with soft texture. Hence, in some sorters material is collected in containers filled with water. Sorting and washing can be combined in one operation.

Sorting by size or shape sometimes is done manually using special calibrators. This is done for material, which must be calibrated by two dimensions. Example is cucumber and gherkin processing. Both are sorted by diameter and length. It can be done mechanically but the damage to the material is extensive.

Color sorting is done either manually or by image analysis. Manual sorting is applied to large objects like fruits and vegetables, and is done by comparison with color standards. Image analysis is also applied to sort large objects by color. The sorted material is mostly packed and sold. Material subjected to freezing or drying may also undergo color sorting. Hence, this sorting is aimed to fulfill expectations of the consumer. In some instances color sorting is aimed to assure quality of the final product. For example, in sesame seeds husk is bitter and must be removed to assure high quality of halva. Another example is separation of bruised apple or fungi infected potatoes. Material, which not matched the standard, is removed by the jest of air actuated by computer.

The above-described methods of sorting divide the material into fractions on the physical basis. However, separation of the material into fractions with different quality is also required. It is done by grading. In many instances, size and weight of the material are related to the quality and sorting is sufficient as a method of grading. There are some material features, which cannot be assayed by size, shape or weight. Freshness of eggs, ripeness of fruits, crumb structure in bread, baking properties of flour are examples of quality features, which cannot be divided into classes by sorting. Grading in most cases must be done by a laboratory tests. In some cases, physical properties can be used for machine grading. It was already mentioned that small green peas is sweeter than the large one. Density of peas is related to its tenderness. Hence, grading can be done using brines of varying density. Grading is a process difficult to realize in the on-line fashion.

3.1.5. Liquid Expression

Expression of liquid fraction from plant material is used in fruit and oil processing. The process is usually preceded by size reduction and heat treatment. The cells must be disrupted to release liquid; however, a bed of pressed material must be sufficiently porous to allow free flowing of the expressed liquid. To reduce viscosity of oil, heating of disintegrated seeds is, in some cases, applied. In processing of some fruit juices heating and enzymatic treatment are used to avoid jellification of concentrated product. In wine making grape expression is preceded by maceration, during which native enzymes hydrolyze pectins. It results in higher yield and better color and taste of juice.

Expression is done in batch presses such as tank press or hydraulic ram press or in continuous presses. In tank press, fruit pulp is fed into horizontal cylinder in which a plastic bag is axially mounted. Air is pumped into the bag, which expands and exerts pressure onto pulp. The tank can be rotated to loosen the pulp and facilitate removal of press residue. In hydraulic ram press fruit pulp placed in cloth bags is stacked one over another. The bags are separated by plastic ribbed plates to facilitate liquid flow. The pressure gradually increases due to lowering of pressure plate. The juice is collected at the base of the press. This type of presses is used for fruit juice expression.

Continuous presses are designed as belt presses, screw presses and roller presses. In belt presses aperture between two belts decreases along and disintegrated material is squeezed. In screw presses in a horizontal cylinder, helical screw is rotated. The pitch of the screw flights gradually decreases towards the discharge and exerts higher and higher pressure on the pulp. Screw presses are used to express oil from oil seeds. The roller press is built of two cylinders in between which the pulp is fed. To facilitate liquid flow the cylinders are grooved. The press residue is removed with doctor blades.

Batch presses allow better expression of liquid from the disintegrated material, because of higher pressures applied. In continuous presses, the press residue still contains substantial quantities of liquid and further processing is required. In case of oil seeds extraction is applied.

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Biographical Sketch

Piotr P. Lewicki is a 1961graduate of Warsaw University of Life Sciences, Faculty of Food Technology. The degree of Doctor of Science he received in 1969 from Massachusetts Institute of Technology, Cambridge, Mass., USA. Studying at MIT Piotr P. Lewicki took his major in food science and minor in chemical engineering. In 1975 he defended habilitation thesis and in 1976 he was nominated associate professor in food engineering. .In 1982 Piotr P. Lewicki was nominated full professor of food engineering.

In the years 1962 - 2008 he was employed by the Warsaw University of Life Sciences in Warsaw. In 1978 Piotr P. Lewicki was appointed the head of the Department of Food Engineering in the Faculty of Food Technology. At that time he was also deputy Dean for student affairs in the Faculty. In the years 1981-1984 he was Dean of the Faculty and during the years 1987-1990 he was appointed a deputy-rector (vice-president) of the University. In 2008 Piotr P. Lewicki has taken the position of the director of the Institute of Food Technology in the State College of Computer Science and Business Administration in Łomża.

Piotr P. Lewicki was a visiting professor of food engineering in the University of Minnesota, St. Paul, USA (1976-1977), in Bundesforschrungsanstalt für Ernährung in Karlsruhe, Germany (1991) and in Universidad Nacional de San Agustin de Arequipa in Peru (2001, 2003).

Piotr P. Lewicki is an editor and co-author of instruction manuals for students and two textbooks on food engineering (four editions) and design of food processing plant (two editions). He has done translation of few professional books from English to Polish. In total he published over 250 publications in Polish and international scientific journals.

Piotr P. Lewicki is a member of the Committee of Food Science of the Polish Academy of Sciences, the Societas Sientiarum ac Litterarum Varsoviensis (Warsaw Scientific Society), Food Working Party of the European Association of Chemical Engineers and The International Academy of Food science and Technology. He is on the editorial board of Journal of Food Engineering (Esevier), International Journal of Food Properties (Marcel Dekker) and Polish Journal of Food and Nutritional Sciences (Polish Academy of Sciences).