A Review on Early Writing Materials: Genesis, Evolution, Industrial Production, and Diversification of Use

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This review of the literature features the fundamentals of papermaking and its history. First, writing substrates other than paper, as well as similar to paper, are discussed. Then, issues related to the invention of the technology of paper and paperboard production as we know it today are presented. Subsequently, facts related to the key achievements in pulp and paper technology that enabled the mass production of these products are described. Finally, examples of papers and processed products (not only papermaking) that significantly expanded the scope of production of pulp and paper industry – also greatly improving people's daily lives – are provided. The article concludes by highlighting the long historical journey toward obtaining a writing substrate with optimal properties — namely, paper. It is proposed to divide the period of diversification of the applications of pulps, paper, and paperboards into *1st generation diversification* and *2nd generation diversification*, the latter corresponding to the contemporary times, i.e. the period in which due to the reduction in the production of writing and printing papers, the paper industry is intensively looking for new applications for papermaking pulps, papers, and cardboards.

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PROLOGUE

Writing substrates were invented out of the need to preserve and disseminate facts, thoughts, images, knowledge, and to obtain the possibility of correspondence between people. These possibilities played a significant role in the civilizational development of humanity as a result of enabling the implementation of education on a mass scale.

To this day, one of the best writing substrates is paper, which is produced from fibrous papermaking pulps obtained from wood, waste paper, and non-wood plants. The invention of this material and the fibrous semi-finished product used for its production was not a coincidence. Rather, it came as the result of many attempts consisting of using various other writing substrates, the characteristics of which, despite the considerable dissemination of some of them in certain periods of the past, did not allow them to be used by wide circles of human societies to such a large extent as in the case of paper.

In addition to the best suitability of paper for writing purposes, its superiority over other writing substrates also results from:

- The possibility of producing it from naturally renewable plant fibres available in many countries of the world;
- Its low price;

- The possibility of its relatively easy processing back into paper and paperboard, *i.e.*, recycling;
- Its general biodegradability in the natural environment;
- The possibility of diversification of the use of this product to produce a number of different products and processed products (including non-papermaking) with properties and applications different from paper (Fig. 1).

Fig. 1. Set of contemporary processed papermaking products (author's photo)

The above features of paper mean that the production of papermaking pulps, hundreds of types of paper and paperboards, and processed paper and paperboard products in the world remains at a high level. Contributions to this high usage of papermaking products include the high per capita consumption in highly developed countries, ongoing civilization development of societies in many countries of the world, people's population growth, and the recognition of these products as one of the best substitutes for products made of synthetic polymers.

Therefore, knowledge of the history of the use of various writing substrates by humanity to record information and their evolution to paper, the development of technology for the production of papermaking intermediates, paper, and paperboard, and the possibility of diversifying the use of these substrates may be of great importance in the author's opinion in the process of educating not only papermaking engineers but also engineers of innovative market products.

This study is precisely a compilation of information on these topics, presenting the information obtained mainly from articles in papermaking journals and on websites, covering a relatively wide range of educational topics.

THE FIRST NON-PAPER WRITING MATERIALS

The first writing substrates can be divided into non-portable and portable types (McGovern 1974).

Non-portable Substrates

Humans began recording information in the form of images in different parts of the world 40,000 to 50 000 years ago (Aubert *et al*. 2019, Oktaviana *et al*. 2024). At that time, popular writing surface included cave walls, which are a classic example of immobile writing surfaces (McGovern 1974).

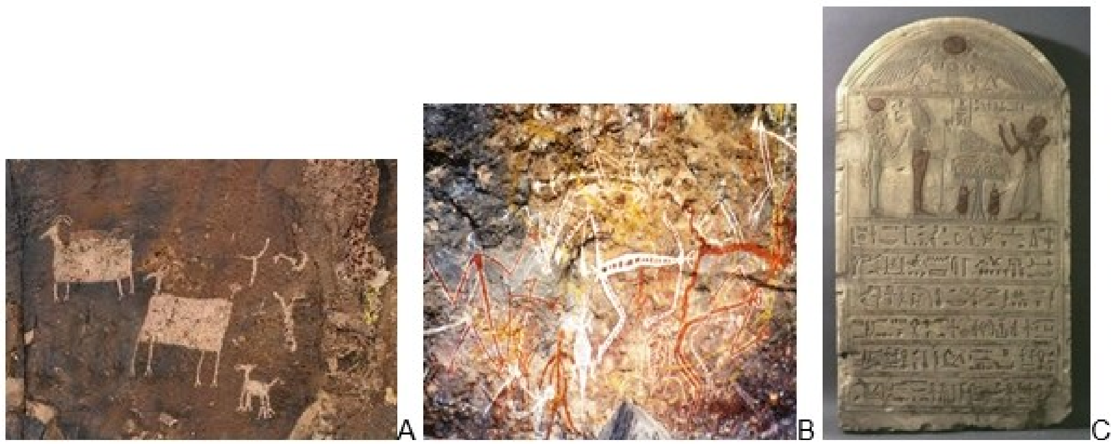


Fig. 2. Rock art in the Altamira cave in Spain (A) (Outline Designs 2025), drawings of strange creatures from the Sego Canyon (B) (Wikipedia1 2024), and a stone table with Egyptian hieroglyphs (C) (Snyder 2024) (author's computer painting based on references)

These written materials are of great importance, as they make it possible to obtain information about the lives of these human groups. Examples include rock drawings found in the Altamira cave in Spain, containing, for example, animal silhouettes painted by primitive people 13 to 35 thousand years ago (Fig. 2A), mysterious geoglyphs made on the Nazca plateau in Peru, and drawings of strange creatures suggesting their unearthly origin in the Sego Canyon in Utah (USA) from 7.5 thousand years ago (Fig. 2B). Much later, already in the era of the Egyptian state, and later, sandstone, limestone and marble tables, walls of columns, temples, and statues were the popular substrate for recording important texts of high seriousness requiring durability. Examples include the text of the Ten Commandments, Egyptian notes, the first parts of the Bible, and the Marmor Parium found on the Greek island of Paros engraved on these types of writing substrates (Fig. 2C). Inscriptions on this type of surface were made by stonemasons using chisels and arrowheads used to carve round letters (McGovern 1974; Meleczyńska 1974; Węgłowski and Przeździecka 1979; Szkolnictwo 2025).

Portable Substrates

Clay tablets

The driving force behind the invention of more versatile portable writing media was the invention of written language around 3300 BCE, although recent research indicates that written elements of human speech (writing signs Y, I, •) as signs of communication may have been in use as early as from 37,000 to 13,000 BC (Bacon *et al*. 2023).

One of the first portable writing surfaces that played a significant role in the spread of indirect forms of interpersonal communication and the archiving of historical events was rectangular clay tablets (Fig. 3) (Taylor and Cartwright 2011; Jean *et al*. 2024).

Fig. 3. Clay tablet with information written on it (authors' computer painting based on Wikipedia2 2024), postage stamp showing another clay tablet (author's photos), and a drawing showing the subsequent stages of making clay tablets (author's drawing based on Jean *et al*. 2024)

This writing material began to be used in Mesopotamia around the 4th century BC. Their production consisted of clay sourcing, clay processing (levigation, folding, rolling, vegetal tempering), tablet shaping, the inscriptions' handwriting, and drying or low- or high-firing (Taylor and Cartwright 2011; Jean *et al*. 2024). The text intended for writing was embossed on these plates when they were yet wet with a special triangular stylus, and after writing them down, they were dried or fired to fix them; thus, they were very durable but unfortunately disposable. These tablets were used to write documents, letters, and notes. It was inconvenient that longer texts required a whole collection of relatively heavy tablets, as well as marking their order. However, the importance of this writing material is very high. They were commonly used in large quantities. Some fragments of the Bible were written on them (Muszkowski 1947; McGovern 1974; Węgłowski and Przezdziecka 1979).

Leaves

In ancient times, leaves of broad-leaved plants were also used to record information (Fig. 4). For example, the Egyptians and Romans used leaves of the fan palm (*Phoenix dactylifera*) and the olive tree (*Olea europaea*) for this purpose, while the Hindus used leaves of the aloe vera (*Aquilaria agallocha*), the palmyra tree (*Borassus flabellifer* L.), or the talipot palm (*Corypha umbraculifera* L.).

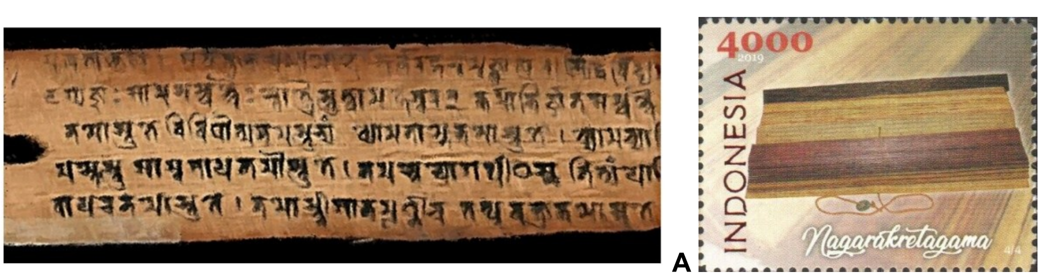


Fig. 4. A written, previously suitable, prepared palm leaf (author's computer painting based on Wikipedia3 2024) and postage stamp showing palm leaves book prepared for writing (A)

In India the history of writing on palm leaves dates from the famous Sanskrit scholar Paniny-rishee, who lived approximately 4161 years ago (Anderson 1991; Padmakumar *et al*. 2003; Wikipedia3 2024). These leaves were prepared for writing using different methods. For example, in the case of *Corypha umbraculifera*, is it: drying in the sun; stripping the leaflets; cutting to size (*e.g.*, 34 × 5 cm); rubbing with sesame oil; keeping in the shade for two to three days; boiling with rice; keeping in the shade for a week; and oiling again. By this method the leaflet will be rendered more resistant, and it will last longer. Writing can be applied then to the leaf surfaces with ink made of charcoal and oil using an iron, silver, or brass stylus, which cuts the upper cuticle of the leaf, and hence the letters remain on the leaf. Then, the printed leaves were bound at the edges into books, the covers of which were made of boards. This was a relatively fragile writing material but widely used in India (Muszkowski 1947; McGovern 1974; Padmakumar *at al*. 2003). Palm leaves were used from the beginning of the creation of Buddhism in India as a writing material for the Buddhist manuscripts. They were used to record actual and mythical Buddhist narratives as well as other information such as traditional medicine methods, astrological maps, prayers, ancestral legends, *etc.* Laos has a huge collection of palm leaf manuscripts dating back to the ancient Kingdom of Lan Xang in the 15th century. The collection is kept in 2,800 Buddhist Wats' Ho Tai (libraries) all over Laos. In addition to religious texts, the manuscripts contain many works in fields such as history, traditional law, poetry, legends, traditional customs, traditional medicine, grammar, lexicography, *etc.* The "Lao-German Preservation of Lao Manuscripts Programme" works to preserve and digitise the old Lao palm leaf manuscripts (Yayasan 2025).

Tree Bark, Wooden Tablets, Metal Plates, Ivory, Fragments of Pottery, Animal Skins, Canvas, and Silk

Birch bark (*Betula utilis*, Himalayan birch) (Fig. 5) was used to record information in India (Padmakumar *at al*. 2003).

A B

Fig. 5. Inscribed birch bark (author's computer painting based on Wikipedia4 2024) and postage stamp showing the message from Жизномира to Микуле written on birch bark tablet in XII century (author's photo)

It was found to be suitable for writing short and unimportant notes. This bark was rubbed with oil from the inside and polished, which made it soft and shiny. This writing material was called bhurja. White birch bark (*Betula papyrifera*) was also used by

American Indians to record drawings (Muszkowski 1947; Shenoy 2016; Wikipedia4 2024). As Pedieu *et al*. (2008) report, bark of this species has two different parts. The outer bark has a paper-like texture with several layers, while the inner bark has a granular form. The bark of some trees for writing was also used by the ancient Romans, which they called "*liber*," and this is the root for the word "*library*" (Anderson 1991).

In many cultures (*e.g.*, Hellenic), wooden tablets (Fig. 6A) and metal tablets (copper, brass, lead, tin, and bronze) (Fig. 6B) were used to record information (Ancient-origins 2024).

Fig. 6. Tablets for recording information: Roman wooden (A) (Judson 2021), metal (B) (MacDermott 2016), Chinese bamboo (C) (Effros 2025), and wax (D) (Judson 2021) (author's computer paintings based on references cited)

In Greece, flat wooden boards were used for writing, which were polished and whitened with chalk. It was called "*leukoma*" in Greece and "*album*" in Rome (Muszkowski 1947). Today, leukometers are devices for determining the whiteness of paper. In Chinese culture (until 256 BC), the equivalents of wooden tablets were bamboo boards a few inches long and wide enough to write a column of text (notes, receipts, wills, reports) (Fig. 6C). Wooden tablets were used in schools as the school notebooks (lined wooden tablets) and in everyday life, while metal tablets were used to record important documents (McGovern 1974; Węgłowski and Przedziecka 1979). Wooden tablets could be slightly hollowed and filled with wax (Fig. 6D), which could be erased or melted to be written again. The inscriptions on these tablets were engraved with a type of pen called a *stylus*. Hence, in French, the fountain pen is called a "*stylograph*" or "*stylo*: (Judson 2021; Effros 2025). Wooden or wax tablets were bound with string. Placed one on top of the other that they formed a volume resembling a tree trunk. For this reason, such a collection was called "caudex" (originally in Latin meaning "block of wood" or "tree trunk") (Judson 2021; Effros 2025), which, in the case of making wooden tablets from beech wood, was called in Old English "*bōc codex*; the term which later evolved into the word "*book"* (Entymonline 2025). Metal plates were used to record short or very important texts, such as spells and magical texts, *e.g.*, those placed in the grave of the deceased, inscriptions dedicated to the Gods, military diplomas, *etc*., and sometimes letters (McGovern 1974; Meleczyńska 1974; Węgłowski and Przedziecka 1979).

Fig. 7. An ivory tablet from Egypt from around 3100 to 2890 BC (A) (Fernandez 2025), and an ostracon/ostraka (B) (Wikipedia5 2024) (author's computer paintings based on references cited)

Animal skin tanned with tannin was also used to record information in various regions of the world (Central America, Assyria, Persia, India, and Cyprus). The first mentions of writing on leather come from Egypt (first half of the third millennium BC), Assyria and Greece [here books were called leather (*diphtheria*)], and Palestine (Jewish translation of the Holy Scripture into Greek. After recording, the long pieces of skin were rolled into rolls and tied with a strap (Fig. 8A) (Muszkowski 1947; Libiszowski 1955; Meleczyńska 1974; McGovern 1974; Outline Designs 2025). Linen was a writing material used for writing by the Etruscans (Etruscan *Liber/Libri Linteus* or *Linen rolls*), as mentioned by Licinius Macer, an author from the 2nd century BC; in Egypt (written cloths for wrapping mummies); and in ancient Rome (journals of Emperor Aurelian) (Fig. 8B). The use of this writing medium was limited, however, due to the greater popularity of papyrus for writing (Muszkowski 1947; Meleczyńska 1974; Commons 2024). Further examples of the use of fabrics to record information are those from India. Bhattacharya (2022) reports that (in the Indian context) Nearchos (4th century BC), an admiral of Alexander's fleet, was the first to mention that the Indians used to write letters on belt-beaten cotton (pata) cloth.

Another type of fabric used to record information was thin silk fabric (fine-weave silk strips), called *zhi* in Chinese. It was used in China to record important official texts, speeches, and regulations (*e.g.*, imperial decrees) due to its high price. Its advantage was its low specific weight, which made it easier to carry than wooden tablets, while its disadvantage was the need to use a brush to record information, which was inconvenient (Winczakiewicz 1957a; Pań Czi-sin 1977; Zhong 1985; Tsien 2004; Leung 2008). The inconvenience of writing on silk due to its pliability the Chinese remedied by forcing together of several such pieces in the manner of fulling, resulting in a significantly stiffer writing material called *fan* paper (Ling 1961; Dąbrowski 2006).

An example of the use of wooden , metal tablets, ivory and porcelain, and tanned leather is the use some of them to record fragments of the Bible, texts contained in the so-called Dead Sea Scrolls, and the Hebrew Scriptures (McGovern 1974).

A B

Fig. 8. Prepared animal skin with text written on it (A) (Outline Designs 2025) and written strips of cloth taken from a mummy (B) (author's computer painting based on Commons 2024)

Papyrus (Egyptian Paper - EP)

In 3rd and 4th century BC, in Egypt, a writing material called Egyptian papyrus began to be used on a larger scale to record information. It was made from the *Cyperus papyrus* L., *Cyperus alopecuroides*, and *Cyperus articulates* plants (Waly 2001), which grew abundantly in the Nile Delta at the time, but came from African countries located lower along the Nile, such as Sudan, Uganda, and Ethiopia. It is a marsh plant, with a triangular stem measuring 25 to 37 mm, growing to a height of 2.5 to 4.0 m, with a stem ending in a plume (Fig. 9A).

A B

Fig. 9. Papyrus growing on the riverbank (A) (Bananalicious 2024) and the stages of its production (La Destiny 2025) (B) (author's computer painting based on references)

The method of making EP consisted of: cleaning the stalk of papyrus plants from the outer layer; cutting it into thin strips; hydrating the strips in water (this activated the natural glue substances present in the papyrus stalks); rolling them to remove the organic material remaining between the fibres and to soften them; arranging these strips so that they overlapped slightly (by about 1 mm); applying a second layer of the same arranged strands crosswise, followed by compression of the two-layer material to glue them together; drying; smoothing with a stone or a piece of ivory; and cutting to the intended width (*e.g.*, 25.0 to 37.5 cm) (Fig. 9B). The finished EP was also saturated with cedar oil, which increased its whiteness and protected it against moisture and insects (Muszkowski 1947; Ragbag 1972; McGovern 1974, 1978; Węgłowski and Przedziecka 1979; McGovern 1982a,b; Waly 2001; Bausch *et al.* 2022; La Destiny 2025).

The sheets obtained in this way were glued into a roll usually composed of around 20 cards, up to 15 m long (sometimes even up to 40 m) using river sludge or flour glue containing drops of vinegar and tightly wound on wooden poles so that it could be embraced with a hand. Its width was approximately 22.5 cm and 12 to 15 cm for normal grade and inferior grade EP, respectively. They were wrapped in a cover and stored in chests called "*bibliotheke*". EP was produced on a large scale from around 3000 BC. Its production also lasted during the years of glory of the Roman Empire and the Byzantine Empire. It was expensive. For two EPs, one had to pay the equivalent of eight times more than a poor Athenian earned daily. It was often written on both sides with a pen made from, for example, *Arundo donax* reed and ink made from soot mixed with gall juice. EP is not regarded as paper because it is not made from individual fibres. It is reported that as many as 7 EP grades were commercially available, of which the grade 7 was only suitable for packaging. The term "*papyrology*" is associated with EP, which deals with the study of notes made on EP in Egypt in the period from 331 BC to 641 CE, when Egypt was taken over by the Arabs. EP is best preserved in Egypt because it is relatively sensitive to moisture. In Europe, EP was still used in the 11th century (these were EPs from the papal chancellery's stocks). Interestingly, in 1982, there was a report on EP production in the Instituto del Papiro (Syracuse, Sicily, Italy), the Institute of Cairo (Egypt), and village of Al-Qaramous in Al-Sharkia Governorat and its use in fine art journals, as a gift and as paper for diplomas, as well as the reintroduction of papyrus to the banks of the lower Nile, where it had not been present for many years (Muszkowski 1947; Ragbag 1972; Meleczyńska 1974; McGovern 1974, 1978, 1982; Węgłowski and Przedziecka 1979; Naiel *et al.* 2024). In the 1950s, one of the oldest EP was a scroll in a museum in Istanbul. Radzimski (1954) writes that it contained the following sentences with telling content: "Oh, times are not what they used to be. Children do not listen to their parents." A written EP scroll can be considered as the form of a book. However, it wasn't a comfortable book to read, as it had to be held in both hands, gradually unrolling the right hand while rewinding the section already read with the left. Returning to a particular section of text was also problematic, requiring scrolling the entire scroll (Meleczyńska 1974).

Parchment

As already mentioned, leather has been used as a writing material for a long time, but at some point in history it was found that the special preparation of skin from young sheep, calves, and goats can improve its properties as a writing material. That is how parchment was invented. The inventor of this writing material is considered to be the king of the city of Pergamon (now Bergama), Emunes II from Asia Minor, who lived in the years 197 to 159 BC, although it is said that less well-finished forms of parchment could have been used earlier. The increase in the popularity of parchment, also known as the membrane of Pergamon, as a writing material was due to the ban on the export of papyrus from Egypt, which was commonly used for writing until the 4th century AD, and because parchment had the advantage over papyrus in that it could be manufactured virtually anywhere. Czerniatowicz (1976) states that from the 4th century onwards in the Byzantine Empire, religious and secular works were written entirely on parchment. It turned out that parchment was more durable than papyrus, could be written on more conveniently on both sides, and it was also more convenient to cut pages from it and form books than from EP. The best parchment (vellum) was made from thin skins of young sheep and goats. These skins were at first kept in a solution of lime in water. Then, hair and meat residues were removed from them. After washing, they were dried by being stretched on frames (Fig. 10A), and then smoothed with pumice, rubbed with a solution of chalk to brighten them, dried again, and smoothed again. Therefore, the hides intended for parchment production were not chemically tanned. Parchments varied in quality. For example, those in the Byzantine Empire before the 6th century were beautifully crafted, smooth, thin, and white, while those from later centuries were more primitive, thicker, and rougher, with distinctly different flesh and top surfaces. The characteristic texture of the parchment surface resulting from the use of animal skin for its production is shown in Fig. 10B (Muszkowski 1947; McGovern 1974; Czerniatowicz 1976; Węgłowski and Przedziecka 1979; Anderson 1991).

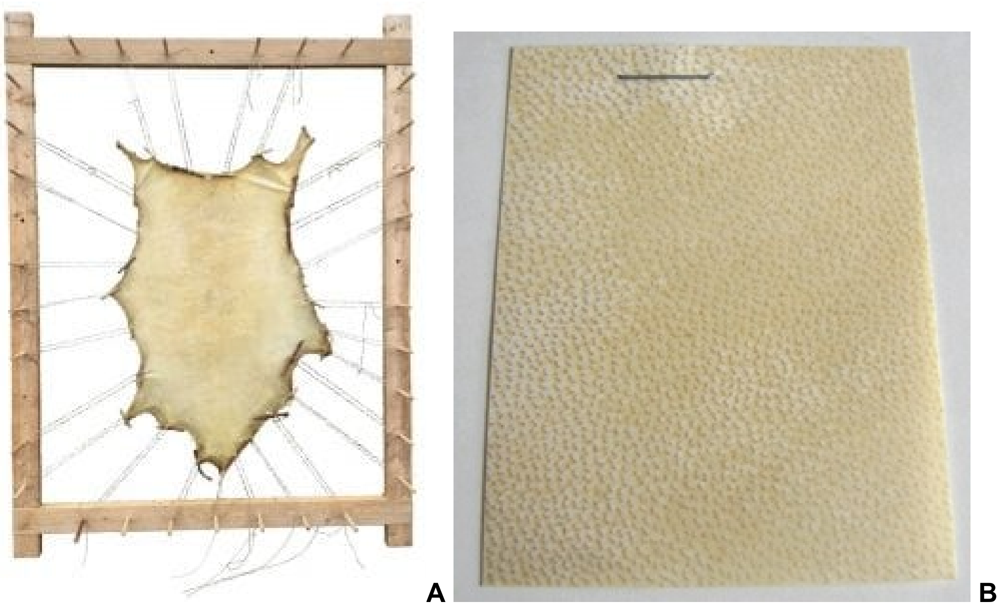


Fig. 10. Drying parchment (A) (author's computer painting based on Blog 2024) and its surface texture (B) (author's photo)

In medieval Europe, parchment was made in monasteries or in craft workshops. It was used for official documents, diplomas, grants, and religious books (Bibles, psalters, and prayer books). Parchment was durable but expensive. Its disadvantage was also its poorer ability than paper to absorb ink. Initially, it had the form of a scroll, but in the early Middle Ages, parchment books called *codices* began to be created. The genesis of their invention was the need to bind the pages of a literary work so that they did not mix with each other (Muszkowski 1947; McGovern 1974; Węgłowski and Przedziecka 1979).

PAPER-LIKE WRITING MATERIALS

Huun, Amatl, and Tapa

Huun (hu'un), amatl (amate paper), and tapa (Fig. 11) can be regarded as primitive forms of paper. They were produced by the Mayas (residents of the Yucatán Peninsula of Mexico), Aztecs (central Mexico), and Polynesians (Pacific Islands) people, respectively (probably the Mayas were the first to produce paper-like writing material). There are known books written on such kind of writing material as the Toltec's "History of Heaven and Earth" (660 A.D.) and the Dresden Codex (900 to 1100 A.D.) Samples of this writing material and a number of books were brought to Europe by the Spanish in the 16th century. The name tapa comes from the southern islands, around Hawaii (Loebner 1972; McGovern 1982a, Sandstrom and Sandstrom 2012; Wikipedia6 2024, Wikipedia7 2024).

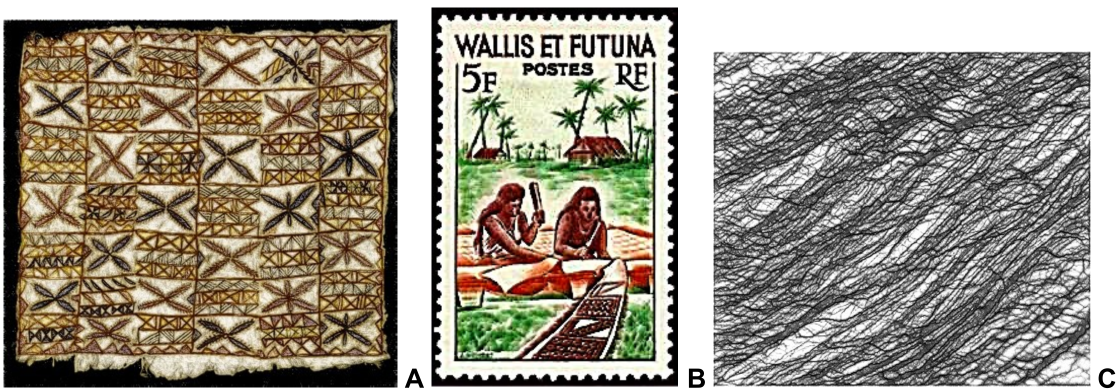


Fig. 11. Tapa type bark fabric (author's computer painting based on Wikipedia6 2024), the postage stamp showing making of tapa (author's computer painting based on original), and look-through of tapa (author's computer drawing based on Dąbrowski 2006)

A more detailed description of tapa-like writing materials production by American Indians was provided by the Spanish physician F. Hernandez. Amatl was made from the bark (i.e. inner bark) of fig trees (copo, amate tree) (*Ficus padifolia*, *Ficus* spec., *Ficus tecolutensis*) and mulberry bushes (*Morus microphylla*, *Morus celtidifolia*). This bark was stacked in piles where a weak fermentation could occur, then it was boiled with the addition of wood ash or lime, and washed. After chemical softening, the bark material was laid on a wooden board in a rectangular layer, on which a second layer was applied in a direction perpendicular to the first. Then, these two layers of bast strips were beaten with a wooden hammer, which caused them to disintegrate, created a "jelly-like" mass on the fibres and the fibres intertwining (Fig. 11B). After drying on a fabric, a paper-like material was obtained without being spun into yarn or any subsequent weaving, one side quite smooth, the other rough and brown or yellowish white in colour. The technique of producing this type of paper-like product was transferred along the equator, because they were also discovered in Madagascar. Tapa-like products differed from paper in that they contained fibres that were not completely separated from each other, intertwined with each other as a result of hitting with a hammer, and were physically-chemically bound to each other to a much lesser extent than in the case of contemporary paper (Fig. 11B). Tapa-like products, apart from being used to record information, were also used to make clothes (so-called bark fabric), carpets and similar products. It is reported that the Aztecs collected extremely rich collections of religious and scientific writings written on amatl. Such products were also used by the Aztec state administration. Unfortunately, on the orders of the first bishop of Mexico, the Spaniard Juan de Zumrraga and fray Diego de Landa, the collections of documents, and scientific and literary works of the Aztecs were burned and, as a result, irretrievably lost (Libiszowski 1955; Zajączkowski 1968; Sandermann 1969; Loebner 1972; Wierzbicki 1975; Dąbrowski 2006).

"Baqiao" Paper and Similar Papers

In China, a fragment of writing material similar to tapa called "Baqiao paper" could be also used for writing, and its production is believed to have been dated to 140 to 87 BCE. Studies have shown that this material consisted of long (67 cm), stiff technical hemp fibres with their fibre walls without fibrillation and bundles of these fibres. This indicates that these had never been cut or mechanically processed to increase their flexibility and degree of fibrillation (Fig. 12A) (Wang and Li 1983). This could be a tapa-like material because Ling (1961) states that in China such bark cloth materials were made in southern region of the country before Tsai Lun era called *ku-pu* paper, *heh-ti* paper or *nieh-ti* paper (there are Chinese records of the third century AD describing *ku-pu* paper) (Dąbrowski 2006).

In China, before the present era, paper-like products with slightly better writing properties than "Baqiao paper" were also produced. These products include "Juyan paper" (Fig. 12A) and "Fufeng paper" (the production of the latter is dated to the years 52 to 6 and 73 to 49 B.C.) (Fig. 12C) (Winczakiewicz 1960; Wang and Li 1983; Zhong 1985). As can be seen from Figs. 12B and 12C, the better quality of the "Juyan and Fufeng papers" resulted from mechanical processing of hemp fibres, as a result of which they underwent some shortening and fibrillation both in 30 to 40% (Wang and Li 1983).

Fig. 12. Fibres of "Bagiao paper" (A), "Juyan paper" and "Fufeng Paper", respectively (computer drawings based on Wang and Li 1983 thanks to courtesy of dr. P. Pełczyński)

The announcement of the discovery of 'a paper sample made before Cai Lun's time' was propagated worldwide also in 2006. McCartney (2006) published some remarks about this event in her short article informing that a scrap of paper made from linen fibre was found by archaeologists picking through an ancient rubbish tip at the Yumen Pass, the gate between China and Central Asia. Measuring just 1.6 square inches, it is believed to have been made in 8 BC, i.e., 113 years earlier than the first known paper. However, the author of this article hasn't found information about the scientific institutions involved in detailed analyses of the fibrous substance found at the Yumen Pass, regarding its fibrous composition, its structure (bark cloth, paper, or anything else), and – first and foremost – its dating.

"Rice" Paper and Silk Paper

Other paper-like products used in China for writing and painting were so-called "rice" paper and silk paper. "Rice" paper was called such because many people believed it was made from rice. In fact, it was made from the coils cut from the pith of stem of the kung-shu, or "rice paper" plant (*Tetrapanax papyrifer*) (Fig. 13A) that grows in Southern China and Taiwan by cutting it tangentially around the perimeter (Fig. 13B), processing them, and joining them together in a method similar to the production of papyrus.

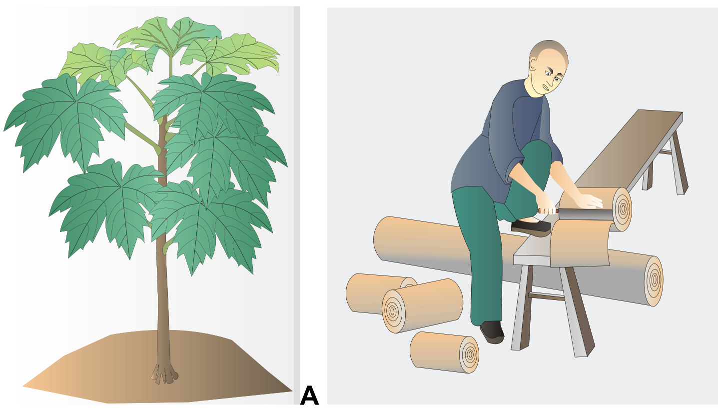


Fig. 13. *Tetrapanax papyrifer* (A) and cutting a sheet of "rice paper" from the stem of this plant (B) (author's computer drawings based on Wikipedia8 2024 and Nesbitt *et al*. 2010, respectively) (author's drawing based on references cited)

This process was facilitated by the fact that the pith of the kung-shu stem contains only 1% lignin (aspen wood has 20.3% and papyrus wood has 13.3%). Sheets of "rice paper" with extremely high whiteness and a fluffy paper structure were mainly used for watercolour painting and creating floral arrangements (McGovern 1974; McGovern 1982a; Hubbe and Bowden 2009).

It is speculated (Winczakiewicz 1960; Ling 1961) that between 206 B.C. to 25 B.C. silk paper could be made, probably from waste silk fibres. These fibres remained on the fabric on which thick layers of silk wool (used in China to protect against the cold) were washed. They had to be gathered, dispersed in water, and lifted out of it in the form of a thin layer by the medium of a moulding mat. It is also mentioned that they could be beaten even before moulding. However, concerning a possible use of silk fibres for making paper in ancient China, Tsien wrote in 1985 that "no actual paper made of pure silk fibres are known to exist, nor is their use documented in literature" (Dąbrowski 2006). Dąbrowski (2020) also doubted the possibility of producing writing material from such silk fibers because experiments he performed in 2020 showed that silk fibres have very low paper-making properties even after beating.

PAPER AND SINGLE-LAYER PAPERBOARD

Chinese Paper

The still insufficient writing properties of the first Chinese writing materials, the development of civilization in China in the times before our era, and the custom of recording information about the most important events in the Chinese state (historiography, chronicles, family histories, chronological tables, biographies) caused the need to invent a writing material better than the "Baqiao, Juyan and Fufeng papers". Officially, based on the chronicle of Hou Han Szu, covering the years of the younger Han dynasty (Eastern Han) (25 to 220 AD), it is stated that this was done around 105 AD by Tsai Lun (or Tsai Ching Chung AD 48 to 121), an official, later minister of the imperial court, who produced the new writing material in three stages. First, obtaining a fibrous intermediate, then moulding paper from a suspension of this intermediate in water using a new mould, and finally subjecting it to drying and surface finishing. There are some doubts as to whether Tsai Lun first used woven old clothes, ropes, and nets woven from hemp (*Cannabis sativa*) and ramie (*Boehmeria nivea*) fibres or the bark of some bast plants, such as *Broussonetia papyrifera* (*Morus papyrifera* L., paper mulberry, ku-shu, "grain tree") and the white mulberry (*Morus alba* L., silk mulberry, white mulberry or *zhi* tree) in the form of strips stripped from the stems of these plants or old clothes, screen curtains, or carpets made from tapa-like materials (McGovern 1982a; Winczakiewicz 1957a; Chang 1964; Ying-Hsing 1967; Loeber 1972; McGovern 1974; Pan Czi-sin 1977). This is because hemp and paper mulberry bast fibers are difficult to distinguish under microscopic examination, as reported by Dąbrowski and Czaplicka (1991).

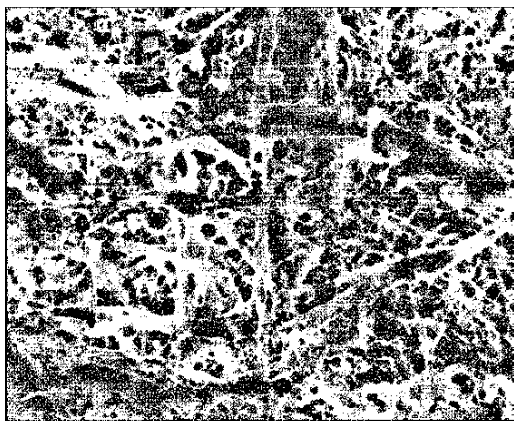


Fig. 14. The structure of the "Hantanpo paper" (author's computer painting based on photo presented in Wang and Li 1983). The structure of this paper material is visibly thickened, resulting from the advanced shortening and fibrillation of the bast plant fibres (author's computer painting based on reference cited)

The version that Tsai Lun used old woven fabrics and fishing nets confirms in some way a fragment of paper found in Hantanpo (Fig. 14) in 1974 in the Wuwei district (Gansu province, China), dating from 150 to 200 AD (*i.e.*, several decades after Tsai Lun). As studies have shown, it was made of hemp fibres shortened to 4 to 5 mm and highly fibrillated (Fig. 14) (Wang and Li 1983).

In turn, the production of paper from the bark of bast plants and products made from tapa-like materials is strongly supported by the probable low availability of woven rags, which would not have been sufficient to explain the large scale of paper production after Tsai Lun era. Rather, the widespread emergence of paper can be explained by the use of raw materials unsuitable for other purposes, such as the bark of the paper mulberry (Tsien 1974; Dąbrowski 2006).

Leaving aside this somewhat academic consideration, it can be said that the technology of production of pulp for papermaking in Tsai Lun's time was similar in both cases. This involved (Winczakiewicz 1957b; Czang 1964; Ying-Hsing 1967; Pań Czi-sin 1977; McGovern 1982a):

- Obtaining the fibrous raw materials.
- Their initial preparation.
- Long-term boiling it in hot water with the addition of wood ash or lime liquor (this process can be considered a prototype of obtaining cellulose pulp by alkaline methods).
- Washing of chemicals from the treated material.
- Careful cleaning bark strands to remove external impurities.
- Mechanically breaking up (macerating) the softened fibrous raw material into single fibres by hand using a mortar and pestle or in a lever stone pestle machine.
- Manual re-cleaning of pulp from the rest of the impurities.

The process is shown in Fig. 15.

Fig. 15. Postage stamps showing pulp making and papermaking in China, *i.e.*, (from the left side in order) collection of stalks of bark plant, boiling of bark strands in wood ash solution, moulding of wet sheet of paper, removing wet paper from the sieve, and drying paper on wood boards in the sun (author's photo)

This procedure led to the separation of complex bast fibres into elementary fibres. Paper made from such fibres much smaller than technical complex fibres was characterised by a greater number of elements per unit of dry material. Thanks to this, better smoothness, strength, brightness, formation and opacity could be achieved in comparison to tapa-like products.

Tsai Lun was supported by the Chinese emperor Juan-sin, who, according to the chronicler Juan Chun (328 to 376), ascended the throne in 102 AD and "did not like entertainment and amusements, and in his house there was always ink and paper, and he worked very diligently" (Winczakiewicz 1960).

Transition to paper production from small elementary bast fibres required the development of an appropriate method of paper formation. Initially, the *floating mould* (called also *wove mould*) method was used for this purpose (Fig. 16A), which consisted of the following steps (Dąbrowski and Czaplicka 1991) (Fig. 16B through 18D):

- Immersing the mould (wooden frame with a fabric bottom) in a vat of water, a pond, or a quiet creek bay in such a way that there is a thin layer of water above the surface of the fabric.
- Placing an appropriate amount of fibre pulp in it.
- Spreading the fibre suspension over the fabric by hand.
- Lifting the mould keeping it in a horizontal position.
- Waiting for water to drain from the wet sheet of paper.
- Smoothing the top surface of the paper by rolling a wooden roller over it.
- Leaving the form aside for the paper to dry.

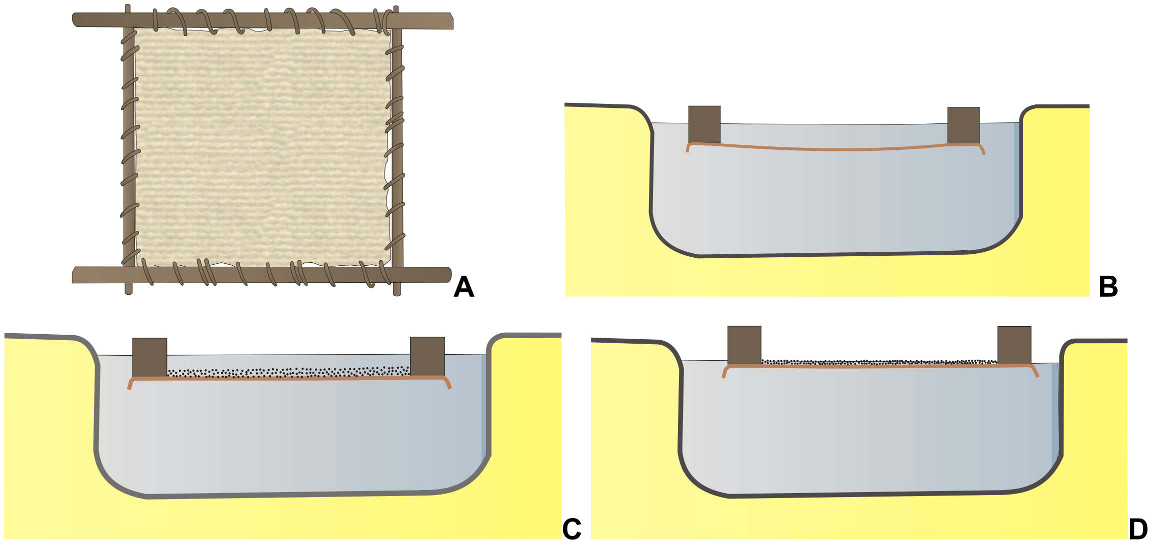


Fig. 16. *Floating mould* (A) and stages of papermaking using this mould *i.e.*, immersing the mould in water (B), spreading the pulp slurry in the mold, and lifting the mould and forming the paper (D) (author's drawings based on Loeber 1972)

However, this method turned out to be too slow. The reason is that the mould is unable to be used again to obtain subsequent sheets of paper and repeat the forming process to obtain thicker sheets of paper. For this reason, the *dipping papermaking mould with removable sieve* was developed. This mould consisted of a flexible mat made of thin, rounded bamboo slivers/rods woven with silk/linen thread, which was then held to a rigid wooden frame with wooden slats to support the sieve. Bamboo slivers/rods were obtained by splitting a bamboo stem lengthwise into thin and long pieces, which were pulled through a slit in the stone to give them uniform thickness and oval shape. On the other hand, a wooden frame can be assembled as shown in Fig. 17 (A to C) (Dąbrowski and Czaplicka 1991):

• Four boards connected, including two shorter and two longer ones.
• Several wooden strips with a circular or triangular cross-section to strengthen the frame, support the sieve, and improve water drainage placed at the level of the shorter sides of the sieve frame.
• Two round wooden sticks (deckle sticks) placed between the longer sides of the sieve to create a certain volume together with them, which was filled with a suspension of fibres during paper drawing.

After forming the layer of fibers on the *movable laid sieve*, it was removed from the frame, and the papermaker placed the formed wet paper on a stack of previously formed sheets, which were then pressed. After removing the wet sheet of paper, the sieve was immediately placed on the frame, and the process of forming a new sheet of paper was repeated. By using such a device, the papermaker could form up to several hundred sheets per day (Loeber 1972; Ow Yang 1997; Dąbrowski and Czaplicka 1991).

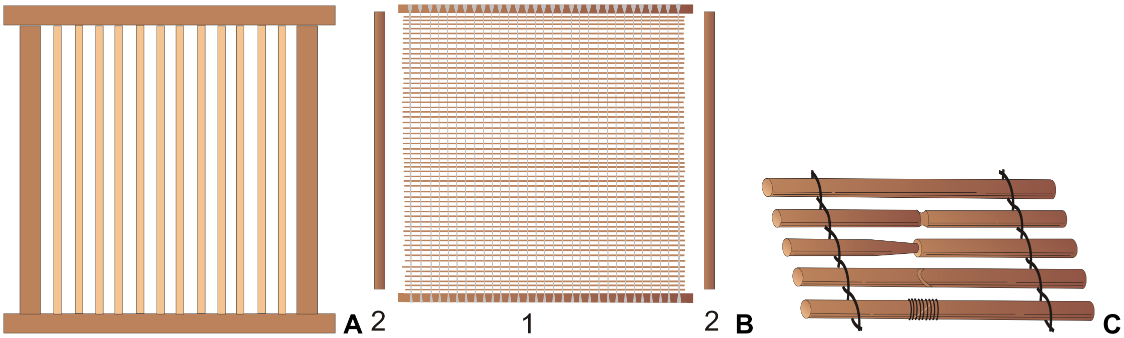


Fig. 17. The wooden frame of the *dipping papermaking mould* with ribs inside it (A), the removable sieve made of thin bamboo rods interwoven with threads (1) and bamboo sticks blocking the sieve on the side (2) (C), and an example of connecting these thin bamboo rods together (author's drawings based on Dąbrowski and Czaplicka 1991)

The introduction, during Tsai Lun's time (including earlier work by unidentified artisans), of the principles of using single fibers for paper production, forming them into a sheet of paper on a sieve from which the wet sheet is then removed and transferred to the next stages of the process, *i.e.*, pressing and drying, created a complete set of technological principles according to which paper is produced in the modern era of Fourdrinier-type of paper machine production.

Fig. 18. Chinese postage stamps depicting: written paper (A) and writing implements: ink brush (B), ink stick (C), and inkstone (D) (author's computer painting based on photo of stamps)

The new writing material, i.e., true paper (Fig. 18A), required the development of writing utensils (Fig. 19B through 19D) (Post 2024). In the period of the Suei (581 to 618 CE) and Tang (618 to 907 CE) dynasties, sandalwood bark, green bamboo shoots, and rice straw were also used for papermaking (Pan Czi-sin 1977; McGovern 1982a). The method of obtaining pulp from young bamboo green shoots was more complex. Its stages included (Chang 1964, 1965; Ying-Hsing 1967; McGovern 1982a):

- Cutting these shoots into pieces of approximately 30 to 60 cm (1 to 2 ft) long.
- Hammering them into coarse fibres and drying in the sun.
- Soaking in solution of lime for 100 days.
- Soaking in clean water for about 7 to 20 days in another pool.
- Smashing with a heavy hammer and washing to remove the green skin and foreign matter.
- Cooking of fibres with lime paste for 48 h for obtaining half-finished pulp.

- Washing of pulp in a pool for 7 days.
- Exposing the pulp spread on mattress to the sun for bleaching it for several days.
- Beating of pulp using with wooden clubs.
- Next bleaching in the sun for another 10 days.
- Secondary cooking it in highly concentrated solution of wood or straw ash.
- Washing and drying in the sun.
- Third cooking of the fibers in a lower concentrated solution of wood or straw ash.
- Final washing.

Even more difficult was the production of fibrous pulp from bamboo stems, which, according to Ow Yang (1997), required subjecting them to 6 years of rotting or keeping them in a lime solution for several months. Using bamboo stems as an example, the Chinese demonstrated that the extraction of fibres from plant materials can also be achieved with regard to highly lignified materials, with a lignin content comparable to that found in wood (Dąbrowski and Czaplicka 1991).

There are reports that fragments of paper were found in Shen-si province showing a sieve drawing on the reverse side. This suggests that paper could have been produced using the T'sai Lun method somewhat earlier, perhaps in the 2nd-3rd century BC during the reign of the West Han dynasty (Winczakiewicz 1960; Tsien 1974; Bil 1980). Hindus also claim to have invented paper by processing old cotton fabrics, claiming that paper was known in India as early as 327 BC, where it could have been used by Buddhist monks to increase people's interest in the Buddhist religion. According to them, it came to China and Turkmenistan from India (Gousaui 1981; Ow Yang 1997). However, it is Tsai Lun who should be considered the inventor of paper and papermaking as it is today, *i.e.*, made from completely separated plant fibres by immersing a mould in a suspension of plant fibres, thin, durable, with properties ideally suited for writing (Winczakiewicz 1960) [(similarly to James Watt, who is credited for inventing the steam engine, despite the fact that some inventors earlier demonstrated more primitive machines (Zhong 1985)], despite that in all probability for making 'true paper' he employed the elements of both the older technologies of making earlier writing materials (Dąbrowski 2006).

In the third century AD in China, wooden and bamboo tablets were largely replaced by paper, which was due to the already good mastery of the art of its production. The following can be cited as examples of the development of papermaking techniques and technologies (Winczakiewicz 1957; Chang 1965; Ying-Hsing 1967; Loeber 1972):

- Production of papermaking moulds made of thin and polished bamboo rods sewn crosswise with silk threads with an inter-rib gap of 0.3 mm and several gaps of 40 to 50/inch.
- Use of suspending large moulds on ropes.
- Use of an additive to the fibrous suspension of pectin glue from the Jan-tao-ten plant (Motungkua - *Abelmoschus manihot Medi*c), thereby reducing the tendency of long fibres to intertwine in the fibrous suspension and sizing the paper.
- Filling and dyeing of paper.
- Use of additives protecting the paper against insects.

Such advances enabled the extension of the scope of the paper's use in the 7th and 8th centuries to include the production of hats, clothing, underwear, sheets, mosquito nets, curtains, partitions, screens, tiles, and even armament (Tsien 1974).

According to Winczakiewicz (1957b), in the 1850s in China, paper production from the bark of white mulberry (*Morus alba*, silk mulberry) was already factory-based. On this scale, so-called Chinese tissue paper with a basis weight of 9 to 18 g/m^2 was produced for album dividers, lampshades, curtains, and napkins. This product was of a craft and industrial nature. First, the raw material was cut into pieces 20 to 25 mm long and rinsed in a river. Then, it was subjected to soda pulping under the conditions: water module 6:1, t = 145 °C, time – 3 h, amount of alkali 22% as NaOH (including 1/3 Na_2S). The pulp yield from the raw material was only 23%. After pulping, the raw material was transferred to the beaters, where 40 kg hammers broke it into fibres, simultaneously squeezing out the black liquor. Then, the pulp was processed in beating device for washing and light beating for 60 min. Bleaching was carried out with calcium hypochlorite. The yield of the bleached pulp from raw material was only 16% (Winczakiewicz 1957b).

Origin of Word "Paper"

The name paper comes from the Greek word papyrus, but its origin is also believed to be in the Egyptian term used for a material monopolized by the pharaoh, referred to in Egyptian as *pharaoh*, and in hieroglyphic transcription as p;pr-', and in the Coptic word pa-prro, meaning royal (Fig. 19A). The term *papier* in Polish was borrowed from Western Europe, especially Old French, where paper was referred to exactly as in Polish, *i.e.*, *papier* (McGovern 1978). In China, paper was named *zhi* as silk woven writing material with the left half of the character representing silk (Fig. 19B). After announcement of Tsai Lun's invention another Chinese character for paper came into use and was also pronounced *zhi* with the 'cloth' radical replacing the former 'silk' radical. However, as the years went by the former character took the predominant position (Zhong 1985).

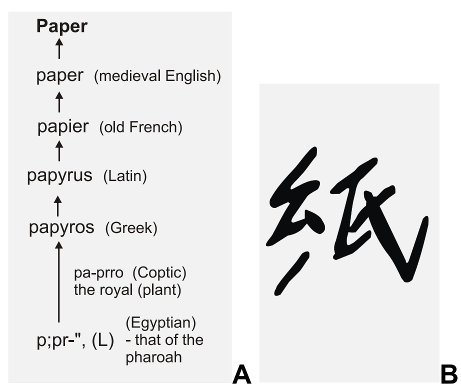


Fig. 19. Origin of the word "paper" (author's drawing based on McGovern 1978) (A) and the Chinese character *zhi* meaning 'true' paper and silk woven writing material (B) (author's drawing based on Zhong 1985)

Japanese Paper

From China, the art of papermaking passed to Korea (370 AD) and Japan (610 AD), where it is still made on an artisanal scale today. In the second half of the 20th century there were still many small family paper mills in this country, located in mountainous regions, where suitable bast plants and clean water from mountain streams are available. In Japan, traditional papermaking uses bark from the stems of shrubs such as:

- *Broussonetia papyrifera* (syn. *Morus papyrifera*), known in Japan as kozo (Fig. 20A) and in Western Europe as paper mulberry.
- Korean paperberry (*Broussonetia kazinoki*).
- *Edgeworthia papyrifera*, also known as mitsumata (Fig. 20B).

- and groups of shrubs from the *Wickstroemia* family (*Wickstroemia retusa*, *Wickstroemia canascens* syn. *Diplomorpha sikokiana*), also known as gampi (Fig. 20C) (Szanto *et al*. 1953; Winczakiewicz 1957; Wijato and Zalewski 1958; Narita 1965; Lindberg 1960; Abrams 1963a; Antoszewska-Moneta 1997; Liszewska 1998; Hiromi Paper 2024; Print Day in May 2024).

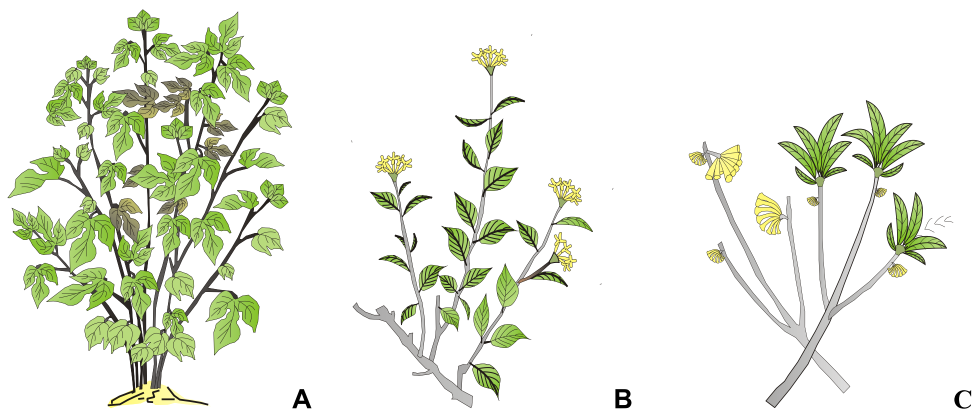


Fig. 20. Kozo (A), gampi (B), mitsumata (C) plants (author's drawing based on Hiromi Paper 2024)

Kozo is currently used to make majority of Japanese paper. This plant occurs wild on the islands of Shikoku and Kyushu. The shrub grows to a height of 3 to 5 m, producing a trunk with a diameter of up to 10 cm. Kozo bark contains fibres 10 to 12 mm long and 14 to 31 µm wide. It has a form similar to cotton, *i.e.*, a twisted strand. The Japanese call it "strong as a man". In 700 AD, these fibres replaced hemp fibres, because kozo can be cultivated. Kozo paper can be easily recognized by its matte appearance, considerable roughness, and exceptionally long fibres, similar to flax. Mitsumata began to be used for papermaking around 614 AD. This plant, which can also be cultivated, has weak fibres described by the Japanese as "femininely soft and docile" and is used to make thin specialty papers similar to cotton papers, such as paper for lampshades, dividers, albums, curtains, napkins, and filters. Mitsumata fibres are shorter than kozo and gampi (3 to 5 mm) and have a width ranging from 7 to 24 µm. They also have insect-repellent properties. Gampi is a plant whose cultivation is most often unsuccessful because its natural habitat is the mountainous areas. That is why it is expensive, and little is used for papermaking. It grows to a height of 1 to 1.5 m. The length of gampi fibres is 5 to 8 (on average 2 to 5) mm, and the width is 20 to 25 µm. The Japanese call gampi fibres noble or aristocratic. Such fibres produce a dense durable paper with a silky, glossy shine and metallic sound, similar to silk paper (Szanto *et al.* 1953; Winczakiewicz 1957; Wijato and Zalewski 1958; Narita 1965; Lindberg 1960; Abrams 1963a; Antoszewska-Moneta 1997; Witkowski 1991; Liszewska 1998; Hiromi Paper 2024).

The first stage of paper production from the bark of Japanese bark-bearing plants (Fig. 21A), also called *washi* in Japan, is the collection of the stems.

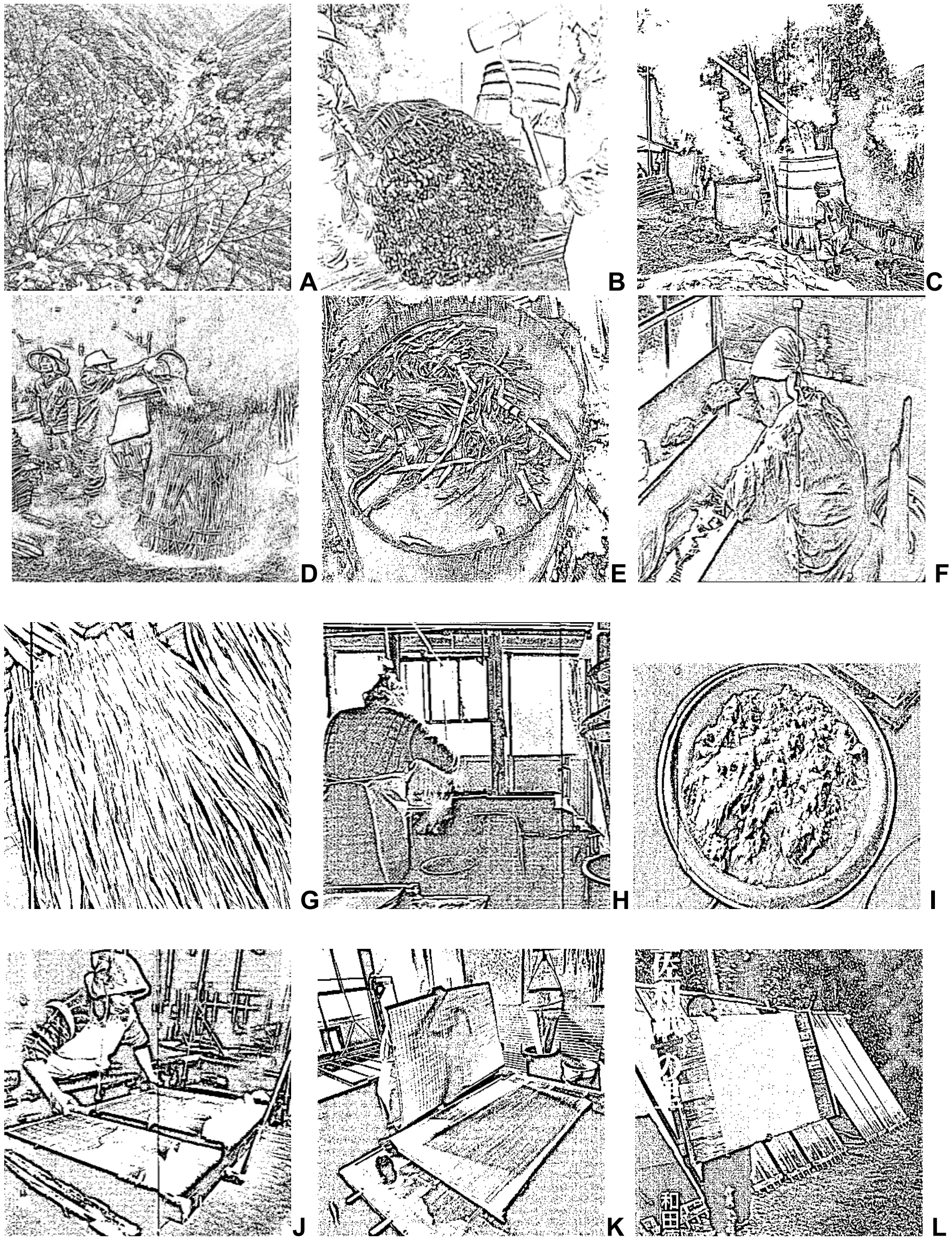


Fig. 21 A-L. Papermaking in a Japanese mountain paper mill. Kozo bushes in the mountains of Japan (A), a sheaf of kozo stems tied with wire (B), steaming kozo stems in a barrel (C), cooling kozo stems after steaming (D), strips of kozo bark peeled from steamed stems (E), removing the dark epidermis from the kozo bark strips by hand (F), drying the cleaned kozo bark strips (G), pounding the kozo bark with a wooden mallet to form fibrous pulp (H), the resulting pulp (I), forming a paper sheet (J), removing the paper from a *movable laid sieve* (K), and drying the paper on wooden boards in the sun (L) (author's computer drawing based on Wada 2003)

They are collected in autumn when the leaves have fallen. Low temperatures are conducive to the production of good paper because of the fewer adverse effects of microorganisms that deteriorate its quality. They are then cut, tied into bundles (Fig. 21B), and steamed in barrels (Fig. 21C) to loosen the bonds between the bark and woody-core. After 1 to 2 h of steaming, the stems are cooled (Fig. 21D) and stripped of their bark (Fig.

21E). Such bark is called *kuro-kawa* (black bark). Then, the strips of bast are cleaned of the dark skin (external epidermis) and the underlying parenchyma layer with a knife (Fig. 21F), rinsed, and dried in the sun in bundles. The cleaned bark is called *shiro-kawa* (in English white bark) (Fig. 21G). To transform the strips of bark into a fibrous mass, they are soaked for 12 h, then boiled in a solution of lye obtained by dissolving wood ash in water (since 1880 mainly in a solution of Na_2CO_3 or even NaOH). The process of boiling in lye from wood ash lasts many hours. The condition of the bark is checked by feel. If it is soft, the boiling process is judged to be finished. The soft strips of bark are washed in a stream in baskets. Holding the bark in flowing water after washing out the lye does not damage the fibres and has a clearly visible effect of whitening the fibres and giving them a natural shine and shade. The partially defibrated bark pulp is then subjected to manual removal of impurity particles, a process called *chiri-tori*, which is done by women. Then, these strands are formed into melon-shaped balls and beaten with a wooden mallet or flat wooden battens (Fig. 21H), which causes the strands to defibrate into a fibrous pulp (Fig. 21L) and also increase the flexibility of the fibres (Szanto *et al*. 1953; Lindberg 1960; Narita 1965; Wada 2003).

In Japan, paper was formed using a mould called *sugeta* that had a structure similar to a Chinese mould. The Japanese are credited with improving the Chinese sieve by introducing a deckle in the form of a frame placed on the frame with a ribbed sieve and attached to this frame, as well as introducing handles attached to the deckle (Fig. 21J). These handles allowed paper to be moulded using very cold water, which slowed down the dewatering of the fibrous suspension on the sieve and increased the efficiency of the plant extracts added to this suspension. Large sieves were hung on ropes to the ceiling. After removing the wet paper sheet from the ribbed sieve (Fig. 22K) it was dried in the sun while being clinging to wooden boards (Fig. 22L) (Szanto *et al.* 1953; Lindberg 1960; Narita 1965, Dąbrowski and Czaplicka 1991).

In Japan, now papers are also made from mixtures of kozo, gampi, and mitsumata, as well as from pulps obtained from other fibrous raw materials, *e.g.*, raffia. The structure of Japanese paper made from kozo, gampi, and raffia fibres is shown in Fig. 22A and 23B.

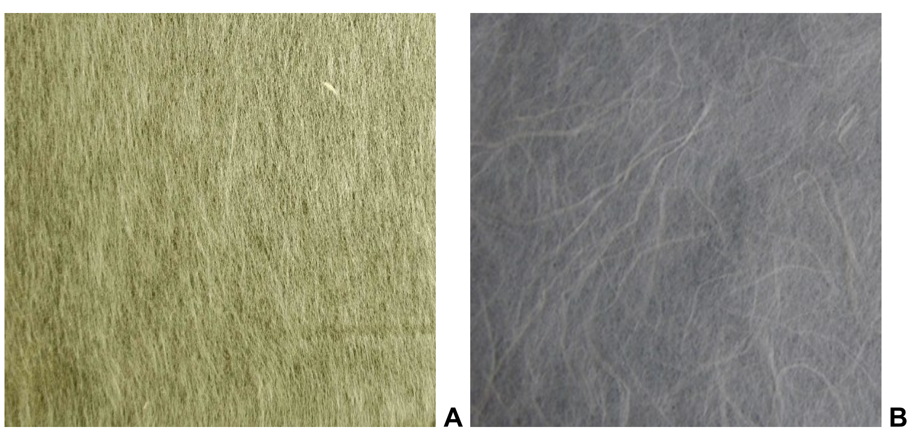


Fig. 22. Japanese papers: multi-fibre (kozo, gampi) (A) (Ramykultury 2024) and haracute made of raffia fibre (B) (author's photo)

As for the process of forming a sheet of paper, two methods of drawing it are currently used in Japan. The first one, *tame-zuki*, is used to produce thicker papers from short-fibre pulps. It consists of taking successive amounts of pulp suspension onto a sieve

(2 to 3 times) until a layer of the appropriate thickness is obtained, leaving the last portion of the pulp suspension to be cut freely. The second, called *nagashi-zuki*, is used to produce thin, high-strength papers. In the case of this technique, the vatman successively takes certain portions of pulp suspension onto the sieve containing the addition of so-called *neri* (or nori) mucilage and manipulates it, spreading it on it to remove the excess short fibres and leave a thin layer of long fibres, giving the paper high strength. This type of paper, in addition to being used for printing and drawing, can be used to make walls in houses, umbrellas, lampshades, and pieces of clothing (Szanto *et al.* 1953; Lindberg 1960; Narita 1965; Antoszewska-Moneta 1997).

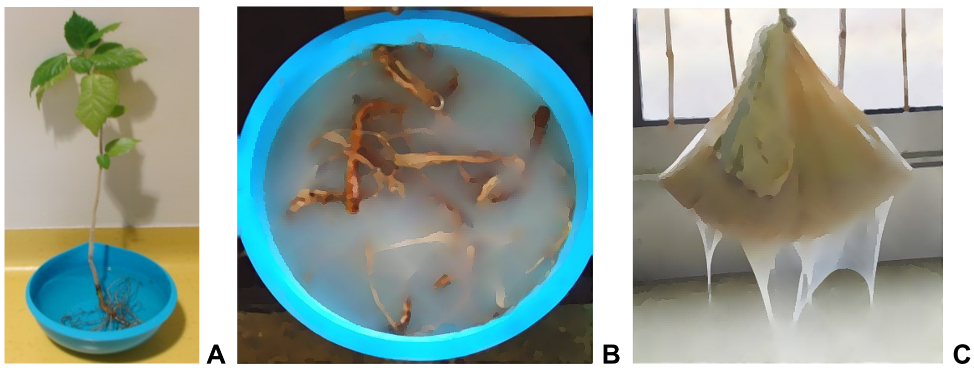


Fig. 23. The plant *Hibiscus manihot* in real together with roots (author's photo, plant provided by P. Adamus), preparation of *neri* from roots of *Torroro-aoi* (B), and filtering *neri* (C) (author's computer painting based on Pride of Japan 2025)

Neri is a sticky, mucilaginous plant extract produced from the roots of the catmia plant (*Hibiscus manihot*) (Fig. 23A), in Japanese called torroro-aoi (Fig. 23B) (Poj 2024) or the bark of nori-utsugi (*Hydrangea paniculata or floribunda*). The mucus-like *neri* added to the pulp suspension:

- Prevents the fibres from gathering in bunches, which allows for obtaining the correct formation of paper;
- Optimizes the rate of drainage of pulp slurry on the mould;
- Improves the strength properties of the paper;
- Prevents wet paper sheets from sticking together during pressing (Szanto *et al.* 1953; Lindberg 1960; Narita 1965; Antoszewska-Moneta 1997).

Another modification used in Japan in the production of *washi* is drying the prepared paper sheets on the walls of metal prisms through which heating steam flows instead of the traditional practice, *i.e.*, on smooth, wooden plates in the air.

Arabic and European Paper

It is said that the Arabs took the art of papermaking from Chinese prisoners who were captured after the battle that took place between Arab and Chinese troops in Turkmenistan on the Thalas River (English Tharaz) in 751, about 700 km east of the city of Samarkand, which the Chinese lost (Anon. 1954; Abrams 1963a; Tsien 1974; McGovern 1987; Libiszowski 1990). However, paper could have reached the Arab people a generation earlier, thanks to the Chinese living in large numbers in Samarkand and convincement of the authorities of the caliphate of the possibility of cutting off the supply of papyrus and the resulting need to find a substitute writing material (Anon. 1954; McGovern 1987) (Fig.

24). In the Arab period, paper began to be made from rags and fabric scraps, including cotton, due to the unavailability of traditional Chinese raw materials for its production. Therefore, it was called linen or rag paper.

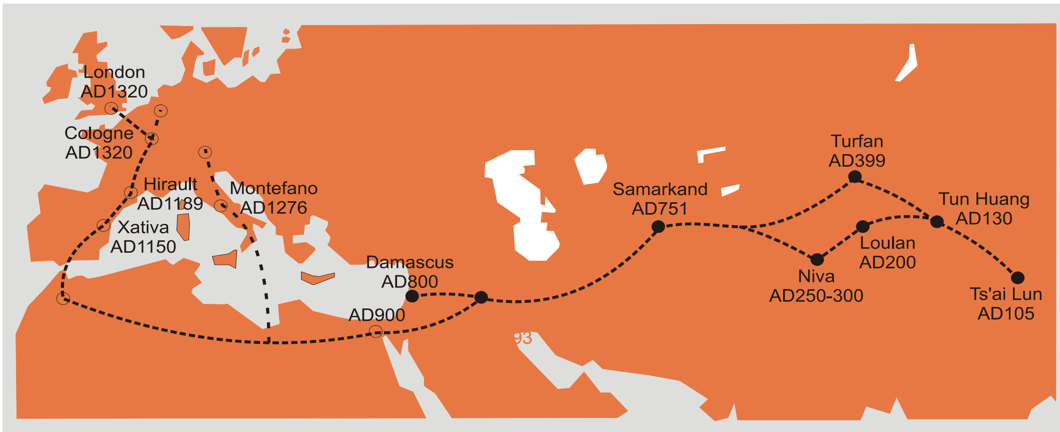


Fig. 24. The path of the art of papermaking from China, to Arab lands, and finally Western Europe (author's drawing)

Fig. 25. A to F: Successive stages of paper production from rags in Europe: A – cutting of previously sorted rags and removing buttons, B – retting (fermentation) them, C – rags' defibreing

in the stampers, D – forming a paper sheet and pressing, E – drying papers in the loft, F – gelatin sizing of papers (author's computer painting based on Barrett 2025)

At that time, the Arabs ruled in Asia Minor, North Africa, and southern Spain. In the 12th century (Fig. 24), they founded the first paper workshops in the Spanish part of Europe in cities such as Capalledes, Xativa (today's San Felipe), Cordoba, and Albarells. The further spread of paper was relatively slow, because it was considered by Christians as the product of short durability, unsuitable for making documents, and of Arab origin (Sarnecki 1956; Abrams 1963a; Astals and Rodés 1983). The literature of the subject also states that the technology of papermaking could have reached Europe directly from Asia, through French war prisoners who were ransomed from Saracen captivity and worked for some time in captivity at papermaking mills in Damascus (Sarnecki 1956).

Another important place in the history of papermaking in Europe was Sicily and the city of Fabriano, where around 1276, a number of paper workshops were established (Marchlewska 1971).

The raw material for paper production in European paper mills was linen and hemp rags, and over time also old linen and hemp ropes and sacks, as well as cotton after the transport from Africa and Asia to Europe became cheaper. Only white rags were used to produce white writing paper (linen, hemp, and cotton linen). Cover paper was made from blue rags, and paper for rough drafts was made from multicoloured rags. The production of paper from rags consisted of several stages, such as removing of buttons, snaps, and seams, cutting the rags into pieces with the help of scythes mounted on tables (Fig. 25A) (*e.g.*, into pieces of 5×7 cm^2) (from 1720 – with a machine similar to a chaff cutter), and then soaking them for 6 weeks in water, sometimes with the addition of lime (Fig. 25B).

During this time, the structure of the complex flax and hemp fibres was biologically or chemically loosened, which facilitated their separation into elementary fibres. The former type of process was called fermentation, maceration, or retting and last long e.g., 11 days. After this process, the rags were transferred to the so-called hammer stamper, *i.e.*, a device used for beating rags pieces for its defibration and washing, which was constructed by craftsmen from the city of Fabriano (Szymczyk 2020) (Fig. 25C). The defibration beating, lasting as long as 12 h for biologically treated rags, was carried out in a stamper through which water flowed. The half-defibrated scraps of rags, called the *rag half-stuff*, were then transferred to the second stamper, in which there was no water flow. In this beater, the fibrous material with the addition of lime was beaten for 24 h, during which the fibres became fibrillated, flattened, and absorbed some of this chemical substance. The pulp obtained was called the proper pulp. The beaters were made of wood. The defibration pounders had iron nail heads. The pounder nests held several kilograms of rags. They were made of stone or wood and equipped with holes closed with a mesh through which water was constantly fed and flowed out. It should be mentioned here that hemp and linen fibres from rags shorten more quickly and are beaten much more easily than the original fibres of these raw materials due to their prior bleaching as well as repeated exposure to sweat, washing, and drying (Sarnecki 1956; Marchlewska 1971).

Then, the obtained fibrous pulp was transferred to a vat, mixed with a paddle, from which paper was moulded (Fig. 25D). Wire moulds (called "laid" mould) were used for hand moulding, consisting of a wooden frame to which brass wires (later copper ones) were attached, creating a kind of ladder supported by thicker wires or wooden strips called supports, creating a structure with the appearance of laid lines. The paper size was determined by means of a deckle, which is a kind of format frame placed on the sieve (Fig.

26A). This type of sieve gave so-called laid paper (Fig. 26B) (Sarnecki 1956; Marchlewska 1971; Dąbrowski and Czaplicka 1991).

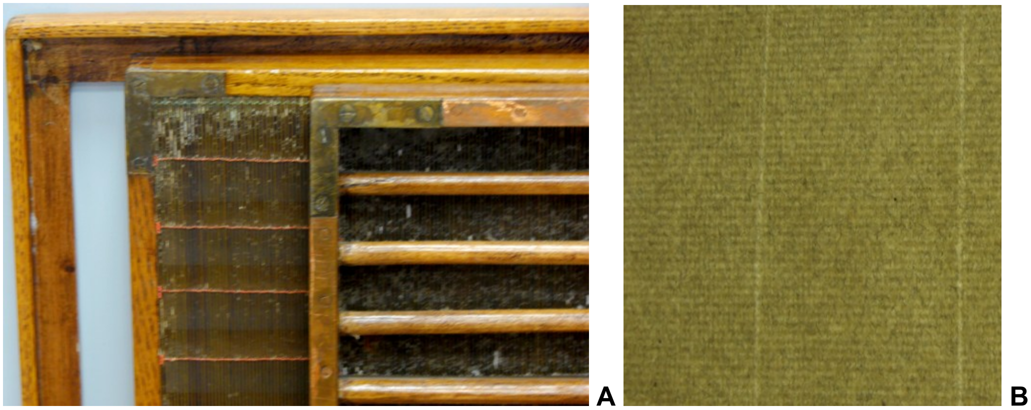


Fig. 26. Construction of a ribbed sieve (A) (authors' photo) and a characteristic transparency of paper obtained from a sieve of this type with laid lines (B) (author's photos)

Alongside these moulds, around 1790, sieves appeared in which the wires were replaced by a metal sieve woven from thin wires, which was so dense that the grates were invisible on the paper. With the help of such moulds, expensive, thin, and smooth *velin* (*vellum*) paper was produced (Dąbrowski and Czaplicka 1991).

The paper on the mould was formed by a vatman. After removing the deckle, the vatman handed the mould to the coachman. He removed the wet sheet of paper from the sieve onto a piece of cloth or wool felt and covered it with the next piece. The sheets of paper laid on the cloth sheets were stacked one on top of the other in a stack of several hundred (*e.g.*, 100 to 261) sheets. The stack was then taken over by a layman, who pressed it in a wooden screw press of the flat type and removed the individual sheets from the felts (Fig. 25E). During the pressing process, water from the wet sheet penetrated the felt, flowed inside it along its surface, and trickled down the edges of the stack of sheets of paper and felt. After pressing, the sheets were dried on strings in drying rooms located in the attic of the paper mill (Fig. 25F).

The dried sheets were then dipped in a gelatin solution (Fig. 25G) or surface coated (Fig. 26C), pressed, dried, and smoothed again (Fig. 25H). The use of gelatin sized the paper and strengthened it. Sometimes the paper was first printed and only then planned, *i.e.*, coated with a weak solution of starch or gelatin and alum containing acidic aluminum salts, which initiated the era of acidic paper (Sarnecki 1956; Astals and Rodés 1983). Twenty-five sheets of paper were called a libra, 20 libras were a ream, and 10 reams were a bale (Siniarska-Czaplicka 1976). The yield of good sheets of paper in the production process, due to the defects occurring during removal and drying, was about 50%.

In the early days of papermaking in Poland, thin paper was produced for letters, as a medium (cultural, writing, and printing) paper for files, thick paper for packaging, and greased paper for windows as a replacement for glass (Żurawski 1962).

It is worth mentioning that paper produced with the addition of lime in the process of beating rags in the stamper contained $CaCO_3$, which alkalized it and constituted an alkaline reserve preventing its acidification and acid degradation, making it durable, which had a positive effect on the state of preservation of old books and documents produced in this way.

In America, the first paper mill was established in 1580 in Calhuacan near Mexico City, and the next one only 110 years later in Wissahickon Creek (Roxborough) near Philadelphia (Pennsylvania) (Wierzbicki 1975).

Along with the use of metal mesh moulds, watermarks for paper were introduced, also known as filigrees (*filun* – wire, *granum* – grains) (Fig. 27A).

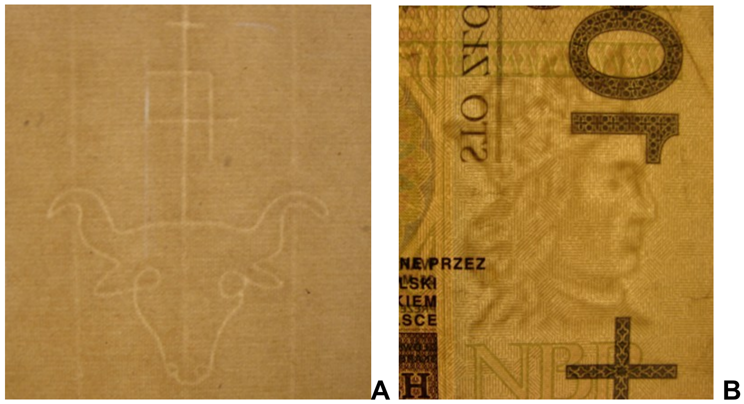


Fig. 27. Linear (A) and light and shade watermark (B) (author's photos)

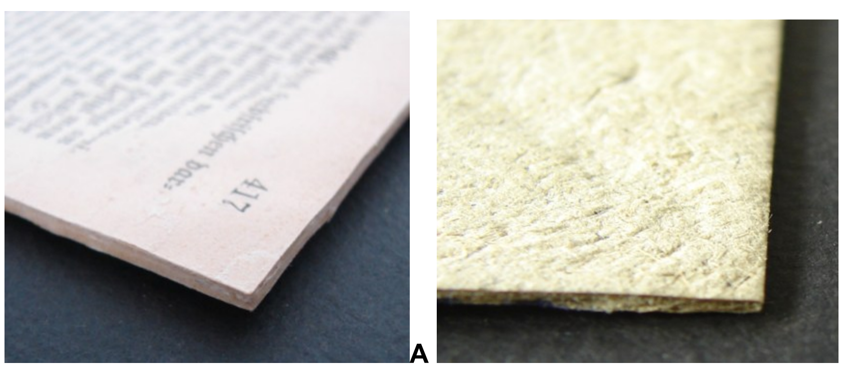
Filigrees were the identification (brand) marks of paper mills, service establishments (*e.g.*, anvil – blacksmith, and boot – shoemaker), types of paper, or family marks. They were produced by weaving an appropriate graphic mark on the surface of a wire screen. This led to the deposition of fewer fibres in the place occupied by the wire and a smaller thickness of paper in that place, which, when exposed to light, revealed lighter lines on a darker, more opaque background. The earliest filigrees were identified in papers produced as early as the 13th century in paper mills located in the town Fabriano near Ancona in Italy. Quite widespread types of filigrees include sacral motifs, a reliquary, a lamb, an angel, and an ox's head. Additional filigree motifs included a crown, a tower, scales, a lily, as well as coats of arms of cities, noble families, and others. Watermarks associated with individual paper mills used in specific periods indicated the origin of the paper and enabled the solution of many historical puzzles (Sarnecki 1958; Abrams 1963b; Siniarska-Czaplicka 1980; Dąbrowski 1990; Historia papieru 2024).

An artistic development of the technique of introducing watermarks into paper was the so-called light and shade filigrees, which allowed, for example, the reproduction of human facial features (Fig. 27 B) (Historia Papieru 2024). The pioneer of this art was the Englishman William Henry Smith, who in 1848 developed a method for producing this type of watermark. The first stage of producing it was to engrave a drawing of the object in a wax plate and cover it with graphite. Then, a layer of copper was applied to the wax reproduction, which was covered with graphite and a second layer of copper. In this way, matrices and counter-dies are obtained. These forms were then covered with lead. Then, a wire sieve was placed between these two forms and pressed in a press. In this way, a relief was created on the screen, which in the process of forming the paper gave a shaded watermark (Abrams 1963b; Marchlewska 1971). In addition to natural watermarks (*i.e.*, those produced during the forming of a sheet or web of paper) the artificial watermarks are also used which are applied to the finished paper.

Single-layer Paperboard

The second important papermaking product is paperboard. Paperboard making exhibits certain distinctive features relative to paper making. The beginnings of solid paperboard originate from China because the Chinese were the first to use thick paper for packaging. In Europe, paperboard began with a change in the method of binding books in the 15th century. At that time, wooden bindings began to be replaced by leather bindings. To stiffen the leather, sheets of waste paper glued together with animal glue were used. In this way the *pasteboard* or *pasted paperboard* was made (Twede 2005). For example, sheets from old, unnecessary account books were used for this purpose.

If after gluing (*e.g.*, 15 layers) the *pasteboard* was pressed, then such paperboard was called *pressed paperboard*. Paperboard was also produced by the method of moulding, called *moulded paperboard*, which can be considered the first solid paperboard. Initially, several sheets of handmade paper were placed between two pieces of cloth, and later the procedure was the same to produce ordinary handmade paper. Later, the entire paperboard was drawn using forms that allowed for taking a larger amount of fibrous suspension and obtaining a sufficiently thick layer of fibres. Thick cloth, ropes, nets, old written papers, paper trimmings, as well as clay and chalk were initially used to produce paperboard pulp. After drying, *moulded paperboard* required straightening the structure of the product, which had become warped due to drying, and smoothing it out. These methods were still used to produce paperboard in the 19th century (Bettendorf 1946; Sarnecki 1976). Examples of *pasteboard* and *moulded paperboard* made by hand are shown in Fig. 28.



A B

Fig. 28. Pasted paperboard (A) made by gluing together pages of a book from 1893 with bone glue and moulded paperboard (B) prepared by author of this article (author's photos)

ACHIEVEMENTS THAT ENABLED INDUSTRIAL PRODUCTION OF PAPERMAKING PRODUCTS

Improvement of the Rag Pulping Process

Producing paper from rags was a long process, especially at the stage of processing in the stamper. Improving its production was an extremely important issue due to the development of science, the growing interest in information exchange, the spread of education, and the improvement of printing and writing methods (in 1714 the Englishman Henry Mill patented the concept of a typewriter).

A significant improvement in the process of producing paper from rags was the construction in the Netherlands in the mid-17th century of a device for pulping them, called a Dutch mill, or colloquially the Hollander beater. Initially, it was an oval vat with a midboard thereby creating circular channel equipped with a heavy cylinders with knives made of metal bars and bed knives. This cylinder, while rotating, forces the suspension of the pulp into the space between the knives and the base plate, thereby kneading it, which causes the rags to defibre, shorten the fibres, fibrillate them, reduce their stiffness, and wash them. The Hollander beater was more efficient than the stamper, and it shortened the process of rags treatment by three times (Fig. 29A) (Gallas 1948; Raczyński 1948; Sawicki 1952).

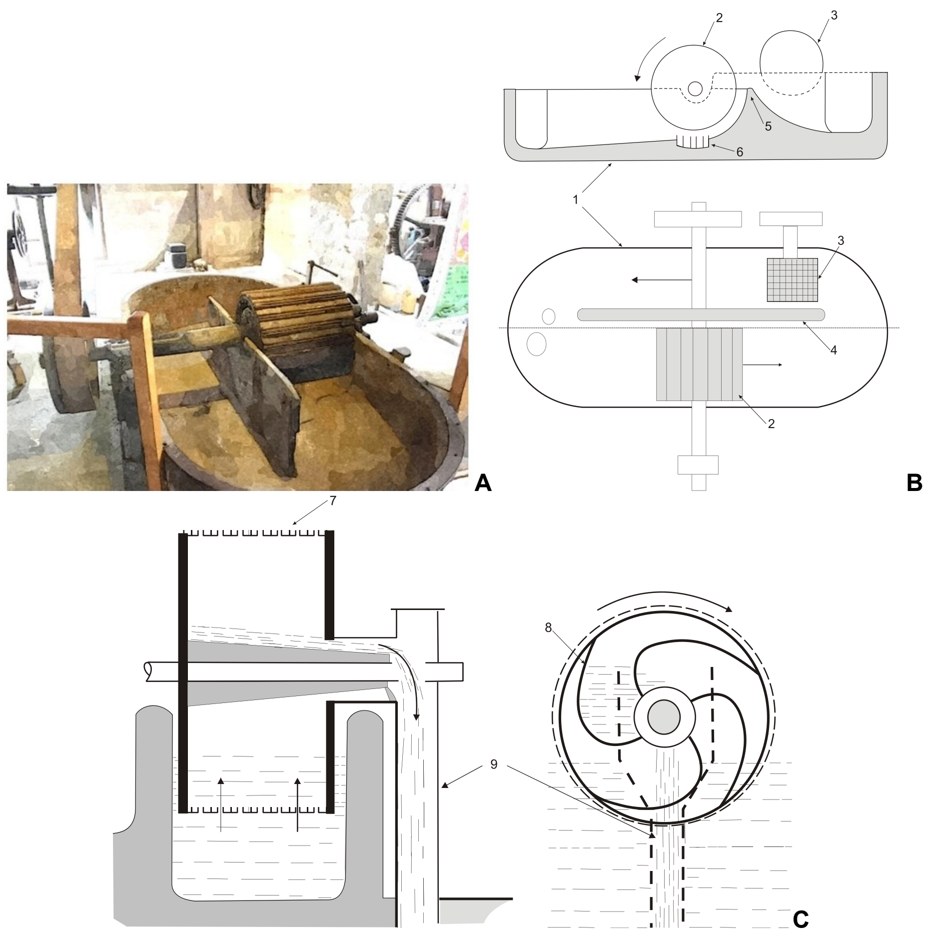


Fig. 29. The tub, knife roller, bed knives, midboard, and drive of a Hollander beater (author's computer painting based on Midi Hide Aways 2016) (A), principle of operation of *half-staff Hollander* for defibration of rags and their washing (B and C) (author's drawings). 1 – vat, 2 – defibreing drum, 3 – washing drum, 4 – midboard, 5 – backfall, 6 – bed knives, 7 – sieve of washing drum, 8 – dipper, 9 – discharge pipe (Baranow and Dobrowolski 1955)

The design of the Hollander beater has been modified in order to use it for various purposes. Among the main designs, it is possible to distinguish the washing hollander (other names *potcher*, *wash hollander*, *wash beater*), *half-staff Hollander (pulping Hollander/beater*, *breaker Hollander/beater*), *general-purpose Hollander* (for the final beating of the rag fibres), and *bleaching Hollander* (*Bellmer Hollander*). They were widely used until the almost complete transition of the paper industry to the production of fibrous pulps from wood and disc and cone refiners for pulp beating (Gallas 1948; Raczyński 1948; Sawicki 1952).

Washing of rag pulps in the *washing Hollander* was performed at their concentration in the tub of 4 to 5%. The rags moved in the device tub and were agitated thanks to the action of the blade/paddle shaft. When the water became dirty, it was removed through the wash/washing drum, and its loss was replenished with clean water. The rags were washed until the water in the device was clean. The washed rags were drained through the discharge pipe into the seepage chamber for dehydration. Washing rags thoroughly is very important because when they are dirty, they are difficult to brighten or cannot be brightened at all (Gallas 1948; Raczyński 1948; McIntosh 1976; Sawicki 1952; Baranow and Dobrowolski 1955).

A *half-staff Hollander* was used only for initial preparation pulp from rags through their defibration and preliminary shortening of their fibres having a degree of freeness not yet sufficient to direct the rag pulp onto the paper machine screen. Such devices were loaded with washed rags to a "consistency" of 2.5 to 5.0% (*e.g.*, 50 kg of rags and 1500 L of water). Unlike a paddle wheel like in a *washing Hollander*, it had a knife shaft instead. Pieces of rags passed between the grinding inserts of this shaft, and the bed knife plate, also equipped with grinding inserts, and were defibrated. These inserts were made of steel, phosphor bronze, and basalt. To shorten the fibres, the distance between the grinding inserts of the knife shaft and the bed knifes was set at a very small distance, *e.g.*, 0.01 mm. In these conditions, each fibre was in contact with the knives, and the fibres were cut, and the pulp obtained was "lean". Over time, when it turned out that the function of producing half-staff rags could be combined with the function of washing rags, the production of *half-staff Hollanders* began, which simultaneously defibred and washed rags additionally (Fig. 29B and C).

As for the *general-purpose Hollander*, it was used to increase the Shopper-Riegler (SR) freeness of rag pulp so that it is ready for further production on the paper machine. In these Hollande beaters, the grinding inserts of the knife shaft were spaced from the inserts of the bed knives by 0.8 to 1 mm, and the pulp concentration was 7 to 8%. The principle of operation of this device is shown in Fig. 30 (Gallas 1948; Raczyński 1948; Sawicki 1952; Baranow and Dobrowolski 1955; McIntosh 1976).

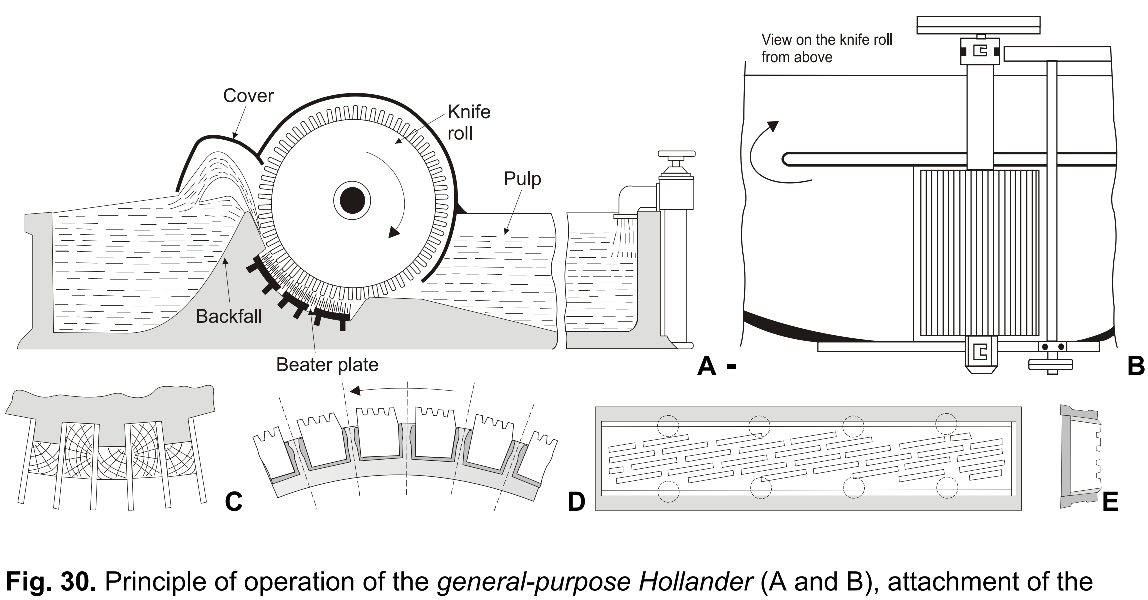


Fig. 30. Principle of operation of the *general-purpose Hollander* (A and B), attachment of the knifes in knife roller in Hollander (C), attachment of basalt knives of the Hollander roller (D), fixing basalt slabs in Hollander plate (author's drawing based on Baranow and Dobrowolski 1955)

In these conditions mainly kneading, expansion, and friction of the fibres against each other occurred, leading over time to their fibrillation and transformation of the pulp from low SR freeness to high SR freeness pulp.

In turn, *bleaching Hollanders* were used for bleaching of fibrous pulps. The main structural elements of these devices were an oval tank made of steel, copper or bronze, lined with chemical-resistant ceramic tiles; partition mounted inside it dividing its interior into two zones; drum equipped with paddles for moving of pulp slurry; and two washing drums for thickening the slurry pulp to the appropriate consistency and filtering the bleaching liquor and pulp washing liquids (Fig. 31) (Gallas 1948; Raczyński 1948; Sawicki 1952; McIntosh 1976). Another type of the Hollander bleacher was the propeller one, in which the movement of the pulp was caused by a propeller or screw agitators (see Fig. 42B).

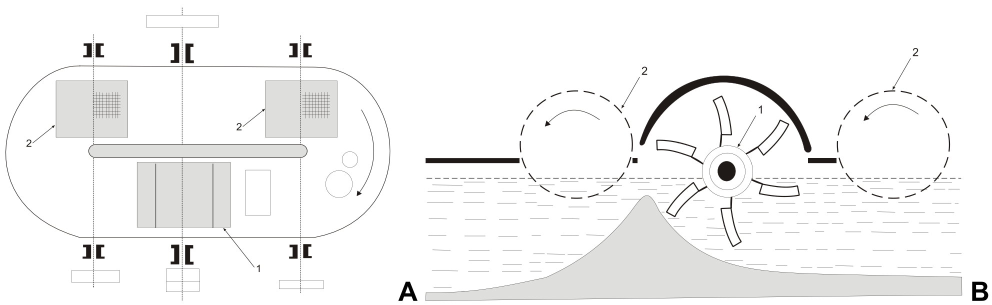


Fig. 31. Principle of operation of bleaching Hollander. 1 – drum equipped with blades, 2 – washing drum (author's drawing based on Baranow and Dobrowolski 1955)

Mechanization of the Paper and Paperboard Production Process

One of the main reasons for undertaking work on the mechanization of paper production in the 19th century was the need to reduce the cost of paper production by increasing its speed (Savill 1983). Until the end of the 18th century, paper was made exclusively by hand, which was expensive, slow, and laborious.

In England and Wales, Scotland, and Ireland, there were 416, 49, and 60 paper mills at that time, respectively. However, production in such craft plants did not keep up with the increase in demand for paper resulting from the development of science, technological progress, the need for education, the increase in number of people, and the economic boom. Paper shortages also resulted from the limited availability of rags, among others, due to the Napoleonic wars. In addition, there were quite numerous conflicts between paper mill employees and employers, which reduced paper production. It is not surprising that here and there concepts of replacing manual work with machine work were born.

The inventor of the paper machine is considered to be the Frenchman Louis-Nicholas Robert (Fig. 32A).

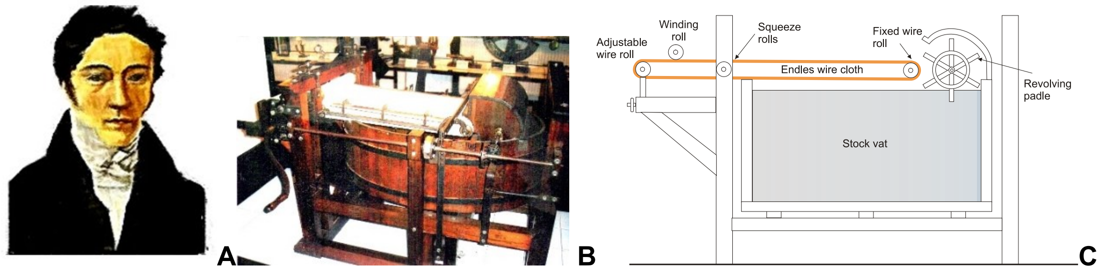


Fig. 32. Ludwik-Nicholas Robert (A) (author's computer painting based on Wikipedia9 2024), replica of Roberts' paper machine (author's photo), and its technical drawing (C) (author's drawing based on Rogut 1991 and Kudryńska 1981)

This man first tried a military career; however, he gave it up and took a job at a paper factory in Essonnes near Paris, where he began work on constructing a paper machine. The owner of the factory was Saint-Léger Didot. He noticed Robert's talent for design and, to curb the workers' increasingly bold demands, began to support his work. Robert built three versions of his machine, the first two of which were unsuccessful. The third version contained a wooden vat with a suspension of pulp, a sieve stretched between two rollers (one of which was adjustable) measuring 64 × 340 cm^2 with a leather side stop, a copper paddle wheel, a curved cover over this wheel, small wringing rollers, and a winding roller from which the web was periodically removed to dry it (Fig. 32B and 32D). The machine produced a web 24 inches wide and 15 m long (Kudryńska 1961; Clapperton 1968; Becker 1972a; Savill 1983; Hansen 1989; Szymczyk 1995; Orzechowska 2007, Wikipedia 9 2024) (Fig. 30A and 30B).

Robert received a prize from the French Minister of the Interior for the construction of the machine, and, on January 18, 1799, a patent for this machine. In 1800, however, he sold this patent for the sum of several dozen thousand francs to the Didot family. S.-L. Didot, seeing no possibility of developing the invention in France, contacted his English brother-in-law John Gamble, who found sponsors, the brothers Henry (Fig. 33A) and Sealy Fourdrinier, who asked the talented mechanic Bryan Donkin to join the team to design a better paper machine than that constructed by N.-L. Robert (Fig. 33B) (Kudryńska 1961; Clapperton 1968; Becker 1972a; Savill 1983; Hansen 1989; Szymczyk 1995; Orzechowska 2007).

Fig. 33. Henry Fourdrinier (A) and Brain Donkin (B) (author's computer drawings)

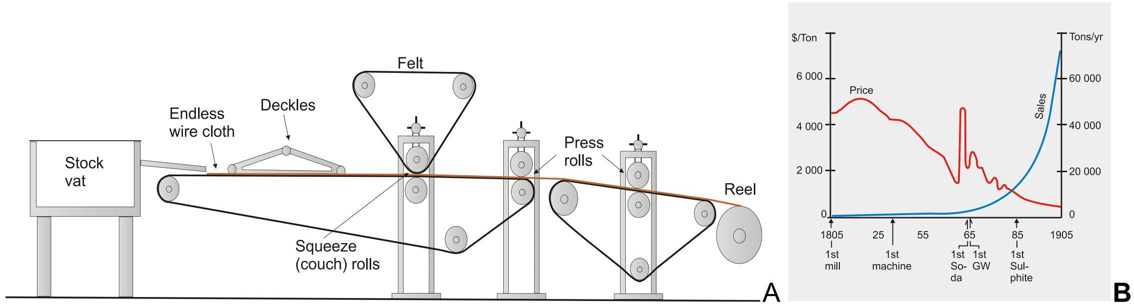


Fig. 34. B. Donkin's paper machine of 1803 (Kudryńska 1961) (author's drawing based on Kudryńska 1961 and Rogut 1991) and reduction of paper production costs in Canada in the 19th century (B) (author's drawing based on Stevens 1981)

A machine of this type began operating at the Frogmore factory in Hertfordshire in 1803. It was characterised by a screen installed outside the vat with the pulp suspension (this suspension flowed from the vat onto the screen from the headbox); pressing the wet paper web in a couch press and then in the roll press; and winding it onto the reel-up (Fig. 34) (Kudryńska 1961; Clapperton 1968; Becker 1972a; Savill 1983; Hansen 1989; Szymczyk 1995; Orzechowska 2007).

The web was then unwound from the reel, cut into sheets, and air-dried. Donkin soon built an improved paper machine, which began producing paper at the Frogmore Mill. From then on, this machine became known colloquially as the Fourdrinier Machine. Nevertheless, for some reason, the Fourdrinier brothers had difficulty in controlling the patent for the paper machine. Donkin took advantage of this by starting his own company, the Bryan Donkin Company, which further improved the paper machine (*e.g.*, by adding a reeling operation), which over the next 50 years, supplied about 200 of these machines to various paper manufacturers. Twede (2005) states that mechanization made paper more plentiful and in 1850 the cost of machine-made paper was 1/8 the cost of hand-made paper. Other companies also started producing paper machines (Kudryńska 1961; Clapperton 1968; Becker 1972; Savill 1983; Hansen 1989; Szymczyk 1995; Orzechowska 2007). According to Leszczyński (1991), paper production in England, which in 1800 amounted to 17,000 tons, increased in 1900 to 650,000 tons, and in 1986 it amounted to 3,941,200 tons.

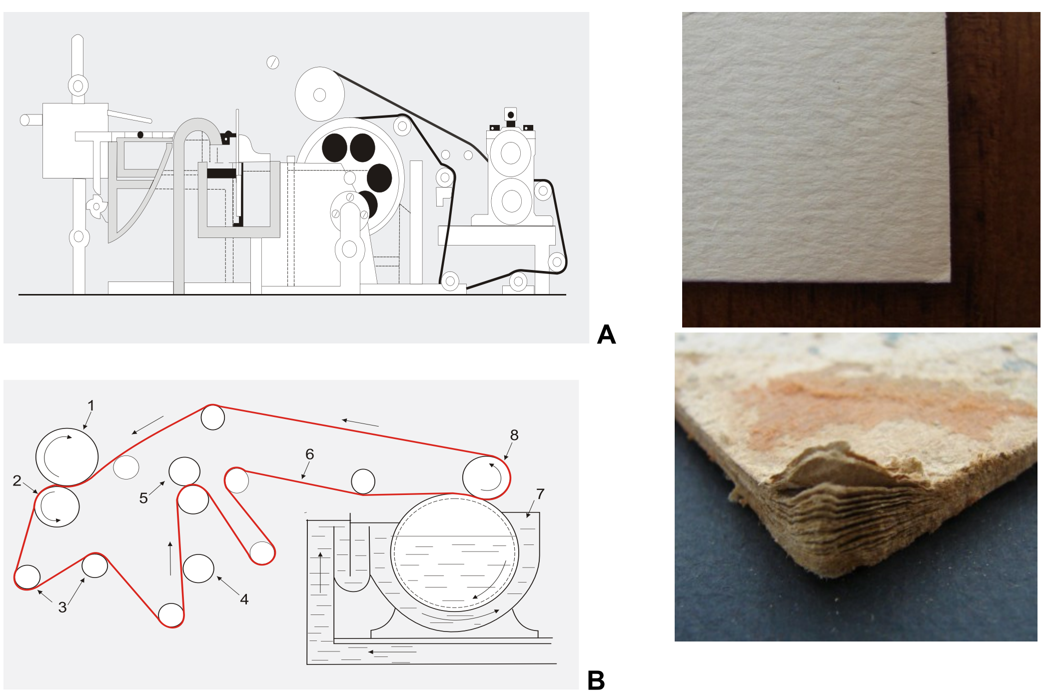
Bryan Donkin and other designers introduced a number of new solutions to the paper machine over the following decades, such as mechanical screen drive, adjustable format limiter, wet press, couch press with a monsoon, heated drying cylinders, dandy, inverse press, knot catcher, and riffler for cleaning the pulp, suction presses, pressure headboxes, electric drives, vacuum web take-up, hydraulic headboxes, synthetic screens, cross-flow, and double-sieve presses, rollers with adjustable camber, and web heating. Over the course of 200 years, the width of paper machines increased from 0.64 m to about 10 m, the operating speed from 5 to 10 m/min to over 2000 m/min, and the production volume of paper mills from 15 to 20 tons to about 1000 tons per day (Rogut 1991). The speed of papermaking on the paper machine was also increased by Moritz Friedrich Illing's invention from 1807, *i.e.*, sizing the paper in the pulp suspension with a rosin glue (Dąbrowski and Czaplicka 1991. Dąbrowski (2009) dates to the same period the first documented use of filler (China clay) in European papermaking in England, which by 1870 became common practice.

According to Stevans (1981) (Fig. 34B), in Canada during the 19st century the introduction of the paper machine reduced the labour costs of papermaking from $1,560 to $560 Canadian, *i.e.*, by 2/3.

The invention of the paper machine and its widespread use marked the end of many handmade paper mills, which were unable to compete with mechanically produced paper. However, not all paper mills produced by the handmade method ceased their operations during the transition to machine-made paper production, as paper still finds buyers. An example of such hand-made paper mills is the paper mill in the Italian town of Fabriano. According to Siniarska-Czaplicka (1979), in the 1970s, in Fabriano there was a plant called Cartiere Pietro Miliani S.P.A., which consisted of four paper mills employing 11,400 people, producing 6.5 thousand tons of straw pulp and rag pulp and 25 thousand tons of paper, such as banknotes, stock papers, bonds, bills of exchange, postage stamps, papers secured against counterfeiting, drawing papers, drafting papers, writing papers, and watermarked papers. The paper mill also produced Roma laid lines handmade paper, made from rags and dyed with natural dyes resistant to light, since the 13th century.

As far as the mechanization of the process of producing solid paperboard is concerned, the possibility of discontinuing the production of sheet paperboard by handicraft methods was made possible in 1824 by John Dickinson, when he demonstrated that this type of paperboard could be produced by his single-cylinder paperboard machine, *i.e.*, a paper machine that:

- Formed a web of fibre network on a cylindrical screen.
- Transferred a layer of this network to a receiving felt.
- Pressed the layer of fibre network together with the felt due using a wringing roller.
- Wound a specified number of layers of compressed wet fibre networks onto a format shaft with a groove on which the paperboard was then cut off after obtaining the appropriate thickness, after which it was stacked, pressed, and dried.



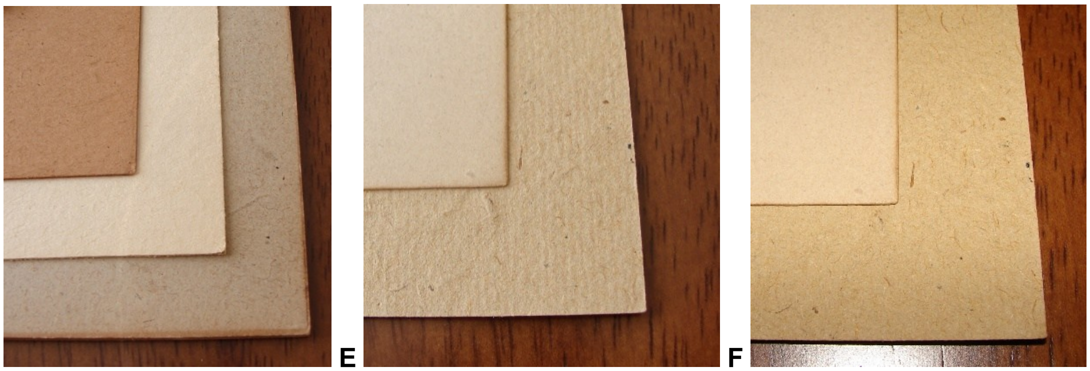


Fig. 35. Single-cylinder paperboard (A) (author's drawing based on Bettendorf 1946) and its operating principle (author's drawing based on Leman 1968); B: 1 – formatting cylinder with groove, 2 – pressing cylinder, 3 – felt guiding rollers, 4 – felt rinsing device, 5 – felt couching rollers, 6 – felt, 7 – forming cylinder, 8 – cylinder of couch; cylinder/wet machine paperboard (C); and corner of a book cover from 1896 showing structure of such paperboard (D) (author's photos); E (going from above) - brown groundwood paperboard, SGW paperboard, and wastepaper paperboard; F - duplex paperboard top side made of kraft pulp and wire side made of SGW; G - duplex paperboard top side made of wastepaper and wire side made of straw pulp (author's photos).

This machine was a development of the design of the cylindrical paper machine for paper production which was presented by Dickinson in 1809 (Bettendorf 1946; Baranow and Dobrowolski 1955; Fuławka 1966; Sarnecki 1976; Twede 2005). Such machine was simpler and less costly than the Fourdrinier type paper machine, but the paper made on it was not equal in quality. Few paperboard cylindrical machines placed in series, in 1870, were used by George A. Shryock in the mill near Chambersburg (Pennsylvania, USA) to produce multi-ply strawboard (Bettendorf 1946; Twede 2005). The drawing of single-cylinder paperboard machine, its operating principle and paperboard obtained using this device are shown in Figs. 35 A, B and C,D, respectively.

The production of solid paperboard began to develop after the advent of machinery for its production. The first trends in its production included the use of inexpensive fiber intermediates for paperboards that did not require good surface properties; the production of two-ply duplex boards (one-sided vat-lined paperboard) with a high-quality, thin, topside and a lower-quality, thicker, backside; and triplex paperboards (three-ply paperboard) with high-quality, thin, bottom and topsides and a lower-quality middle layer, where the surface properties of product required improved properties.

These types of solid board include:

- Brown mechanical pulp paperboard made from brown groundwood (TGW) (Fig. 35E – top sample).
- White mechanical pulp board made of stone groundwood (SGW), which has been shown to be weak in strength, brittle, and absorbent, and was therefore typically used to produce boxes transported for short distances (Fig. 35E – middle sample).
- Waste paper paperboard, characterized by a higher weight and lower flexibility than brown and corrugated board (Fig. 35E – bottom sample).
- Duplex board (one-sided vat-lined paperboard) consisting of two felted layers, the top layer made of high-quality pulp, *e.g.*, cellulose pulp (Fig. 35F).
- Duplex board consisting of two felted layers, the top layer made of recycled paper and the bottom layer made of straw pulp (Fig. 35G).

Replacing Rags with Non-wood pulps, Mechanically Obtained Wood Pulps, and Chemically Obtained Pulps

According to Stevens (1981) (Fig. 34B), in 1820 the cost of one ton of newsprint from rags in Canada was around $5,000.

Fig. 36. Wasp nest made of plant fibres (Wójcik 2023) (A), and the title page of Mathias Koops' book printed on paper made using straw pulp (B) (Graphicarts 2025) (author's drawings based on references cited)

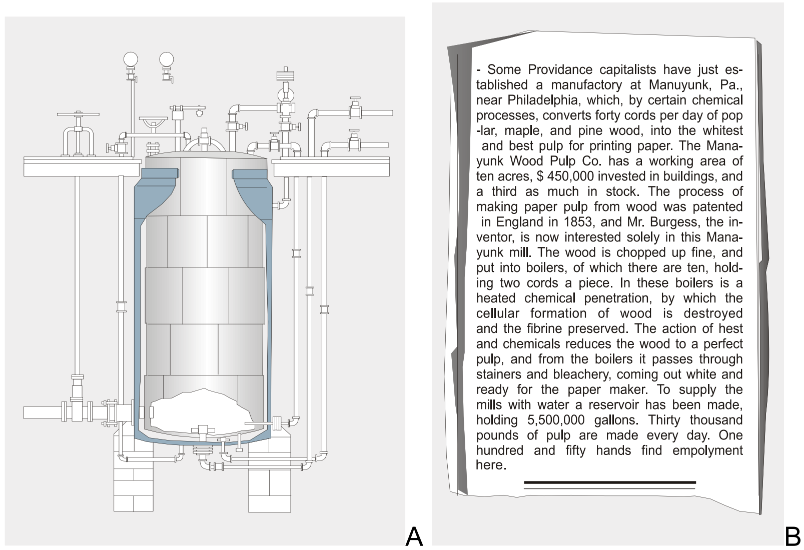
In addition to the cost of labour, this cost was influenced by the operating costs of the paper mill and cost of fibrous intermediate, which amounted to about $1,800 and $1,200, respectively. Thus, to reduce the price of paper, it was necessary to reduce the cost of the fibrous intermediate first. At the beginning of the 18th century (1719), the Frenchman R.A.F. de Réaumour noticed that the material from which wasps make their nests resembled paper (Fig. 36A). Later, McGovern *et al*. (1988) reported that these nests are made by wasps from fibres extracted by these insects from weathered or rotten wood. The fibres are connected in the walls of the wasp nest with a protein glue that is similar in chemical composition to sericin (glue) and fibroin (fibrillar protein, the building block of silk). It is reported that as early as 1707 to 1714, paper was made from straw in the Bogoroditsk paper factory in Russia. In 1765 to 1772 in Germany, the idea of making paper from straw, bast plants, and wasp nests was developed by pastor Jacob Christian Schäffer (Urbański 1953). In 1805, Mathias Koops obtained a patent for making paper from straw, hay, hemp, and flax waste, *etc*. Koops's papermaking process from straw involved cutting it, treating it with cold milk of lime, and then milling it (Urbański 1953; Sarnecki 1970; McGovern and Carpenter 1987). To promote his invention, Koops published a book, *Historical Account of the Substances Which Have Been Used to Describe Events and to Convey Ideas* (Fig. 36B), the second edition of which was printed largely on paper made from straw pulp. Koops produced his pulp in his Straw Paper Manufacturing Company in Millbank, which, however, was quickly auctioned off to cover his previously unpaid debts.

Another example of the use of straw in the 19th century for industrial papermaking is the production of cover and box board from straw pulp in the Honeywell Mill near Chambersburg, Pennsylvania, in 1831, where straw pulp was produced using William Magaw's method of boiling straw in a potash solution, and later lime, which reduces straw to a pulp (Bettendorf 1946; McGovern 1986). The interest of papermakers in straw as a raw material to produce fibrous paper pulps is confirmed by the publication of a book on the subject by Louis Piette in 1838 (Savill 1983). Due to its properties (coarse nature, yellow colour, stiffness, "rattle", and low tearing resistance) straw paper was used mainly for wrapping, butcher paper, packing paper (twisted cones used by grocers), making box board and binder multi-ply board (the use of straw for this purpose was very popular in the USA and has been practiced for several decades) (Twede 2005).

Attempts were also made to produce fibrous pulp from wood using the same method that had been used to produce it from straw. However, these attempts proved unsuccessful because the processing of wood by this method took too long. The breakthrough came in around in 1840s when Friedrich Gottlob Keller in Germany (Fig. 37A) and Charles Fenerty in Canada (Fig. 37B) developed their methods and devices for producing a fibrous papermaking intermediate called stone groundwood (SGW) by grinding short, debarked wood logs with a rough stone roll (Fig. 37C) (McGovern and Carpenter 1987; McGovern *et al*. 1988). Keller sold the rights to the device he invented to Heinrich Voelter, the director of a paper mill in Bautzen (Saxony), who commissioned the production of an industrial model of the device to Johann Matthäus Voith Machinery from Heidenheim in 1847. This enabled the industrial production of this cheap, fibrous intermediate to be launched in Germany in 1850. The invention of pulp was of great importance for the possibility of reducing the price of paper, ensuring its availability to the wide social circles and providing people with access to knowledge in written form and the possibility of universal education. In addition to relatively bright SGW, brown stone groundwood was also produced in the 18th century. This production was initiated by Behrend in 1869, who preceded the process of grinding logs after its steaming, achieving a reduction in the amount of energy for grinding and improvement of the pulp properties, with the negative effect of its brightness. However, this did not disturb the use of this type of pulp to produce paperboard (McGovern and Carpenter 1987, Nostbakken 2017).

Fig. 37. F.G. Keller (A) (author's computer drawing based on Grosse 2025), C. Fenerty (B) (author's photo), and the former inventor's model of the grinder (C) (author's drawing based on Wikiwand 2025)

Another incentive to conduct work on using plant materials other than rags for pulp production were prizes for such inventions. The English magazine *The Times* of London offered a 1000-pound prize for the invention of a cheap substitute for rag pulp (Waugh 1971). One such invention was the pulping of hardwood by boiling it in a sodium hydroxide (NaOH) solution with a concentration of 5.5 g/L in a closed reactor for 6 h at a temperature of 150 °C, proposed by Hew Burgees and Charles Watt in 1851. To prevent water evaporation and excessive alkali concentration increase in the cooking liquor the inventors proposed conducting this process in a pressure reactor (Fig. 38A).



- Some Providance capitalists have just established a manufactory at Manuyunk, Pa., near Philadelphia, which, by certain chemical processes, converts forty cords per day of pop-lar, maple, and pine wood, into the whitest and best pulp for printing paper. The Manayunk Wood Pulp Co. has a working area of ten acres, $ 450,000 invested in buildings, and a third as much in stock. The process of making paper pulp from wood was patented in England in 1853, and Mr. Burgess, the inventor, is now interested solely in this Manayunk mill. The wood is chopped up fine, and put into boilers, of which there are ten, holding two cords a piece. In these boilers is a heated chemical penetration, by which the cellular formation of wood is destroyed and the fibrine preserved. The action of hest and chemicals reduces the wood to a perfect pulp, and from the boilers it passes through stainers and bleachery, coming out white and ready for the paper maker. To supply the mills with water a reservoir has been made, holding 5,500,000 gallons. Thirty thousand pounds of pulp are made every day. One hundred and fifty hands find empolyment here.

Fig. 38. The Marshall's boiler for wood pulping using the soda method (A) and information in 1886 in Boston newspaper about the use of the soda method for pulp production in the Manuyunk mill in Pennsylvania (B) (author's drawing based on Davis 1886)

The positive results of this experiment meant that in 1853 the inventors patented this method, which was called the soda method. However, this method produced low-lignin dark pulps, which caused it not to be immediately adopted in Europe, where paper was made from a mixture of stone groundwood and rag pulps (Surewicz 1990).

The soda method found more fertile ground in the USA, due to the increased duty on paper and the shortage of rags, when in 1860, in Royer's Ford, Pennsylvania started the world's first soda pulp mill (Fig. 38B). However, the lack of chemical regeneration meant that the price of the pulp was yet too high because it included the costs of chemicals. These costs were later reduced somewhat by the introduction of the alkali regeneration process, which initially included only the alkalis draining freely after wood cooking, then the alkalis from washing the defibred pulp from the cooked chips in the digester, and further the alkalis obtained from washing the pulp in diffusers. In Europe, paper pulp was first manufactured by the soda method only in 1866 at the Conemills factory near Lyndey in England (Urbański 1953; Sarnecki 1970; Surewicz 1990; Surewicz 1990; Szymczyk 1994b).

The breakthrough in the industrial-scale production of pulps through advanced delignification of wood occurred in 1867 when Benjamin Chew Tilghman (Fig. 39A) and his brother patented the sulfite (Sy) pulping method of producing highly delignified papermaking pulps, which after the pulping process have brightness of as much as 50 to 60% (Phillips 1943).

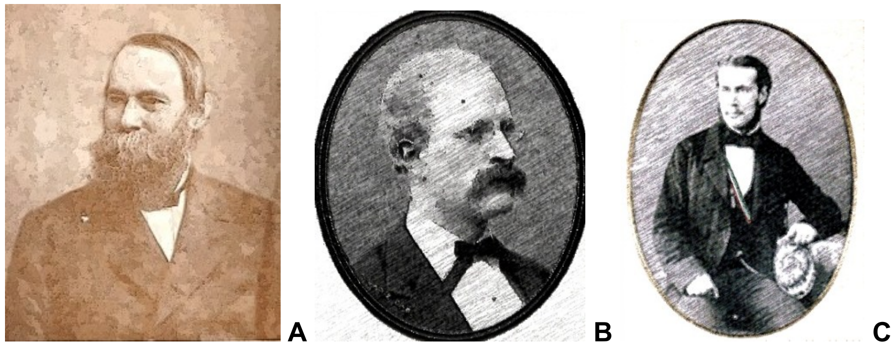


Fig. 39. Drawings of B. C. Tilgman (A) (Wikipedia10 2024), Ekman (B) (Wikiwand 2024) and Mitcherlich (C) (Wikipedia11 2024) (author's computer drawings based on references cited)

Tilghman studied the effect of sulfurous acid on fats in barrels with soft wood bungs that were used to plug the barrels' openings. He noticed that after some time the bungs softened. Later, during a visit to paper mills producing pulp using the soda method, he recalled this observation. However, wood treated with sulfurous acid produced pulp with a reddish tint. Only adding lime to sulfurous acid allowed this colouration of sulfite pulps to be removed. The advantages of the Tilghman method include: the low temperature of the pulping process, *i.e.*, approx. 127 °C and the already mentioned high brightness of the pulps, while the disadvantages included the long time of the pulping process (6 to 8 h), the need to maintain a low pH of the cooking liquid (< 2 units) and saturation of cooking liquor with SO_2, and the lack of possibility of recovering CaO from black liquor (Phillips 1943; Sarnecki 1970; Bogusławski 1974; Surewicz 1994b).

Research on obtaining pulp because of its pulping with solutions of acidic sulfites was also conducted by C. D. Ekman (Fig. 39B), A. Mitscherlich (Fig. 39C), and K. Kellner and E. Ritter. Ekman invented the process of pulping wood by the hydrosulfite method with magnesium hydrosulphite (a chemical compound semi-soluble in water of pH 3-5) and began pulping wood in horizontal cookers heated by means of copper tubes. He was the first in the world to start the production of sulfite pulp with a magnesium base in 1874 in Bergvik (Sweden) and supervised the construction of sulfite pulp factories in England, France, and the USA (Sarnecki 1970).

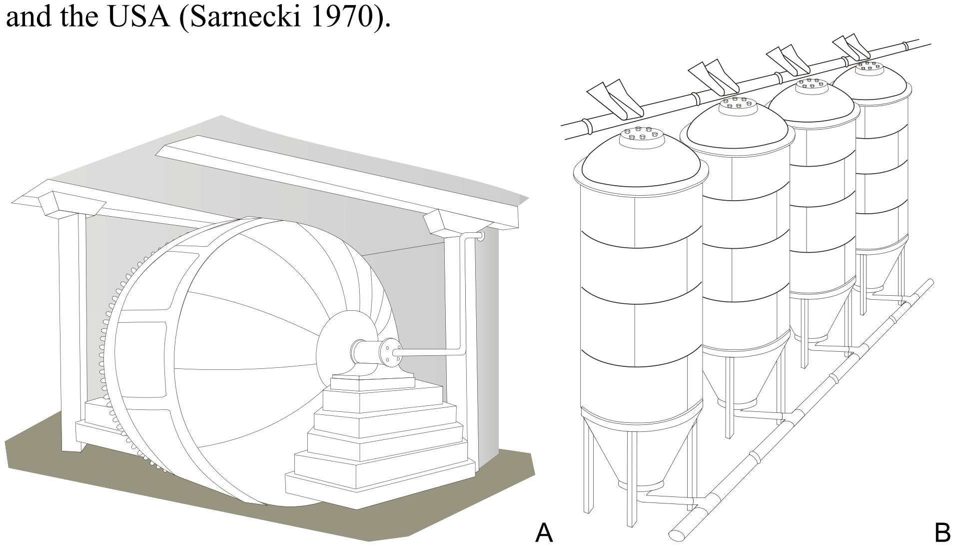


Fig. 40. Horizontal digester (A) and standing digesters (B) (author's' drawing based on Bettendorf 1946)

In turn, Mitscherlich obtained a patent in Germany to produce sulfite pulp and built a factory for this pulp in Münden, Germany, but after two years it was sold, and the patent was withdrawn from Mitscherlich in 1884 due to Tilghman's earlier patent. The contribution of Kellner and Ritter to the development of sulphite pulp production consisted in using standing digesters (Fig. 40B) for pulping using this method, instead of horizontal ones (Fig. 40A). The digesters were heated by direct steam, which enabled the pulping process to be shortened and changed the method of removing the pulped wood from the digester (so-called blowoff) (Sarnecki 1970; Bogusławski 1974).

The production of paper pulps using the Sy method quickly gained great popularity in the world. The cost of producing sulfite pulp was 1/3 of the cost of its production using the soda method. Sulfite pulps also turned out to be stronger than soda pulps (Sarnecki 1970; Kraft 1972; Bogusławski 1974; Surewicz 1994b).

The next alternative solutions that appeared in the technology of wood pulping using the Sy method were the use of ammonium and sodium hydrosulfites, which were chemical compounds completely soluble in water of pH 3 to 5. Sulfite methods using Mg, NH^{4+} and Na bases brought a number of advantages compared to the sulfite method using $Ca(HSO_3)_2$ (chemical compounds insoluble in water of pH 3 to 5) such as: shortening the wood pulping time by 10 to 25%; increasing the pulp yield as a result of reducing the number of knots in digester's pulp; reducing the content of resinous substances in the pulps; reducing problems with boiler deposits, and possibility of recovering Mg and Na bases from black liquors (Kraft 1972; Wandelt 1982).

Currently, hydrosulfite pulp production accounts for less than 10% of the world's pulp production. Sulfite pulps are superior in comparison to kraft pulps in terms of chemical purity, which is important when using them as dissolving pulps. Some of them are also better than kraft pulps for the production of tissues, towels, napkins, and toilet paper, due to the greater softness of the fibres (in the pulping process using the Sy method, the fibres become more flexible as a result of hydrolytic weakening than fibres from alkaline processes) (Myślińska 1962).

The soda method was also modified. In 1879, the engineer C. F. Dahl, employed at the Danziger Holzfaserstoff Fabrik pulp mill in Gdańsk, indirectly introduced sodium sulfide into the soda liquor, which accelerated the pulping of spruce wood compared to the soda method and made it possible to obtain pulps with the highest strength properties yet achieved. It turns out that earlier, in 1853 and 1870, Poole and A. K. Eaton, respectively, demonstrated the possibility of pulping wood with a sodium sulfide solution (Urbański 1953; Waugh 1971; Szymczyk 1997). The first kraft pulp mill, called Munksjö mill, was launched in Jönköping, Sweden. The first pulping was undercooked, and the pulp mill manager ordered the chips to be ground in a disc mill, which led to the first cellulose-like high-yield pulp, which turned out to be very strong, thanks to which it was called "kraftmasse", which in Swedish means "strong cellulose". Because the Swedes exported large quantities of "kraft" pulp, this name for sulphate pulps was adopted all over the world (Urbański 1953; Waugh 1971). Later, it was found that also softer kraft pulps were characterised by better properties than sulfite pulps, which over time, after the development of industrial methods of bleaching dark kraft pulps, led to the abandonment of the production of sulfite pulps and the domination of the market by different kraft pulps.

Fig. 41. Postage stamps showing papermaking plant raw materials used to make paper after it has been produced from rags [(A) - pine *Pinus silvestris*, (B) - birch *Betula papyrifera*, (C) - eucalyptus (*Eucalyptus globulus*), (D) - bamboo, (E) - bagasse, and (F) - cereal straw] (author's photos)

The invention of methods for producing wood pulp, including sulphite and kraft pulps gradually, along with the development of technology and technique, freed the paper industry from rags and rag pulps and made it possible to reduce the cost of raw material for producing 1 ton of paper, *e.g.*, from $1,300 in the case of using rags to about $500, which enabled a significant reduction in the price of 1 ton of paper (Stevens 1981) (Fig. 34B). In this way, the world moved to the era of producing fibrous papermaking pulps from plant raw materials containing much more lignin than natural textile fibres (Lyddon 1963) (Fig. 41).

Development of Bleaching of Papermaking Pulps

The first method of bleaching plant fibres was to expose them to sunlight and water (Fig. 42A). While this method worked well for bleaching fibres that did not contain lignin or contained only a minimal amount of it, it was completely unsuitable for bleaching large quantities of pulp in the dynamically developing papermaking industry. The history of industrial bleaching of fibrous papermaking pulps is primarily associated with the use of chlorine for this purpose. Chlorine was discovered by C. W. Scheele in 1774, and its bleaching properties were discovered by C. L. Bertholett in 1784 (Aścik 1973). Initially, the transport of chlorine or chlorine solution in water posed a major problem. However, in 1779 K. Tennant and K. McIntosh discovered that dry lime absorbs chlorine and transforms it into chlorinated lime (other names "bleaching powder" or "chloride of lime"), which has bleaching properties for textile and delignified plant fibres. This agent was used in pulp mills for bleaching pulps until around 1910, when it was replaced by calcium hypochlorite produced by dissolving chlorine obtained electrochemically from salt on site in these pulp mills in milk of lime. Bleaching of pulp with chlorinated lime or hypochlorites was initially carried out in open tanks, which were replaced by Hollanders because of easier mixing of the pulp suspension in these devices, and then in the *bleaching Hollander*. The latter development enabled bleaching to be carried out at an elevated temperature at a pulp suspension concentration of 5 to 30% (so-called Bellmer bleachers, named after its inventor). As can be seen from Fig. 42B, the device consisted of a vat shaped like a Hollander, two internal partitions, a screw mixer, a hypochlorite supply pipe, and a steam heating system (Rue 1957; Ernest 1959; Kraft 1972; Rapson 1989; Wayman 1998).

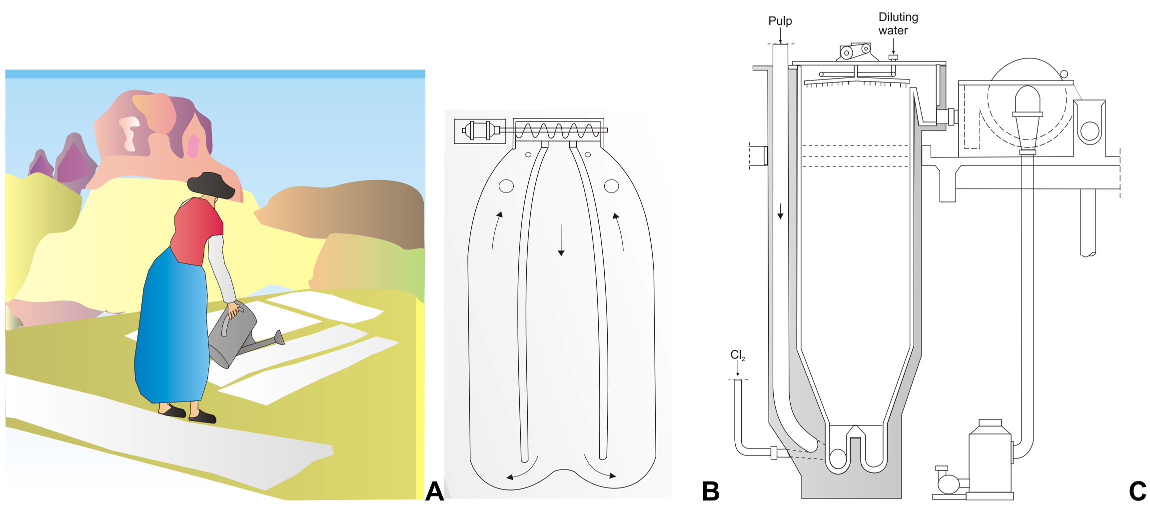


Fig. 42. Bleaching with sunlight and water (A) (Wikipedia12 2024), bleaching Hollander of propeller type, top view (B), and bleaching tower for bleaching pulp with chlorine (C) (Grabowski and Niwiński 1957) (author's drawings based on references cited)

Initially, the bleaching was carried out as a single-stage process at a temperature of 30 to 40 °C, lasting many hours (10 to 14 h) at a pH of the pulp suspension above 9 to 10. Mainly sulfite pulps were subjected to bleaching. Hypochlorites were delivered in barrels, the emptying of which was difficult and dangerous. The invention of the electrochemical method of obtaining chlorine by BASF enabled the production of hypochlorites in pulp mills. After the First World War, bleaching of pulps with hypochlorites began to be carried out in two stages with an inter-stage washing of pulps (HH sequence). This was the so-called period of bleaching powders and hypochlorite stages. In the 1930s, the system of bleaching pulps in pulp mills began to change by introducing bleaching stages in which the pulp was directly exposed to a liquid containing dissolved chlorine, *e.g.*, in the scheme of bleaching with chlorine in the first stage and hypochlorite in the second one (CH sequence).

The introduction of chlorine into industrial practice was made possible only in 1925 by the introduction of closed bleaching towers (Thorne bleaching towers) (Fig. 42C), invented by C. B. Thorne and H. Oftendahl (Rapson 1989) and large pulp pumps, which allowed the introduction of chlorine into the pulp suspension. The introduction of chlorine to the bleaching of pulps necessitated the use of new, non-corrosive materials (steel and alloys, rubber and ceramic linings), new types of pumps, mixers, valves, pipes, washing devices, and vats in pulp mills. These difficulties were overcome in the early 1930s, after which the CEH sequence became a popular bleaching sequence, in which the alkaline extraction stage appeared for the first time, initially referred to as "thermal treatment" (to keep this technological solution a secret), then CEHH. These sequences were used primarily in the bleaching of sulfite pulps and enabled the pulps to be bleached to a brightness of 85%. There was also interest in the bleaching of kraft pulps.

It was found that if the CEH sequence is used for these pulps, their brightness, with the amount of chemicals dosed as for sulfite pulps, can be only 70 to 75%, and with an increased amount of these chemicals – 82 to 83%. In the latter case, however, the pulp fibres were significantly weakened, and the brightness was less resistant to aging. Therefore, before and right after World War II, few kraft pulps were bleached, and the schemes used to reduce the consumption of chemicals had from 5 to even 9 bleaching stages with chlorine and hypochlorites. An example of a bleaching scheme is the CEHEH sequence. The brightness of kraft pulp from such a scheme was about 80 to 85% (Kraft 1972). For the above reasons, this period in technology can be called the period of chlorination and increasing the number of bleaching stages of pulps.

During World War II, restrictions were introduced on the amount of chlorine that pulp mills could use to bleach pulp, as a result of which the brightness of sulfite pulps produced in pulp mills had to be reduced from 90 to 70%. At that time, interest was focused on chlorine dioxide, which was discovered by H. Davy in 1815. The bleaching properties of ClO_2 were discovered by E. Schmidt in 1921. This researcher observed that chlorine dioxide degrades lignin contained in plant fibrous raw materials without significantly affecting polysaccharides (Aścik 1973). Dr. Howard Rapson (Fig. 43A) (Youtube 2024), who in collaboration with M. Wayman developed and launched in 1946 the first industrial continuous chlorine dioxide generator (the method of periodically obtaining ClO_2 was patented in 1938 by Mathieson Chemical Company). This meant that after World War II, in the late 1940s, the first installations for bleaching pulp with chlorine dioxide began to appear in pulp mills. First, bleaching with chlorine dioxide (stage D) was used at the end of pulp bleaching, after stage H. It was found that using one stage of bleaching with this agent in the CHD and CEHD sequences, a pulp can be bleached to a brightness of 85 to 87 and 86 to 88%, respectively (Fig. 43B and 43C). Achieving higher brightness with lower consumption of bleaching chemicals made it possible to use more extensive bleaching sequences, with at least one stage of pulp bleaching with chlorine dioxide. In this way, at the end of the 1950s, kraft pulps began to be bleached according to the CEHDH, CEHHD schemes, and later also CEHDED, CEDD, CEDED, in which the exclusion of hypochlorite bleaching and the insertion of an alkaline extraction stage (E) between stages D made it possible to obtain better brightness stability of pulps and their better strength properties. Kraft pulps with a brightness of approximately 89% were called super-bleached pulps. The CEDED scheme began to distinguish between delignification (CE) and final bleaching (DED) (Rue 1957; Ernest 1959; Kraft 1972; Rapson 1989; Wayman 1998). This period in pulp bleaching technology can therefore be described as the period of superbleached pulps and the abandonment of hypochlorites.

Fig. 43. (A) Dr. Howard Rapson (author's computer drawing based on YouTube 2024); (B) unbleached pulp and (C) the same pulp after bleaching (author's photo)

A further change in pulp bleaching technology occurred in the late 1980s and consisted of eliminating chlorine from the bleaching of these pulps due to the confirmed formation of dioxins in this type of bleaching. It consisted of replacing the degree of chlorination with the oxygen delignification process and continuing further pulp bleaching with chlorine dioxide (ECF technology – Elemental Chlorine Free), chlorine dioxide and oxygen bleaching agents (Light–ECF), or using only the latter (TCF – Totally Chlorine Free). For this reason, this period in bleaching technology can be described as the period of greening pulp bleaching technology.

Later Development of Production of Other Types of Fibrous Papermaking Pulps

Low-strength properties of SGW, shortages of spruce and fir roundwood, and at the same time a large supply of wood waste from sawmills, low yield of kraft and sulfite pulps, and the lack of need to use these pulps for some types of paper products meant that since the interwar period, more attention was paid to the development of technology for producing pulps with a yield from wood raw materials between the yield of SGW and kraft/sulfite pulps.

These pulps include high-yield cellulose-like kraft and sulfite pulps, semi-chemical pulps (*e.g.*, NSSC – Neutral Sulfite Semi-Chemical), refiner mechanical pulps (RMP), chemi-mechanical pulps (CMP, APMP – Alkaline Peroxide Mechanical Pulp), thermomechanical pulps (TMP), and chemi-thermomechanical pulps (CTMP) (Surewicz 1990). The former, with a wood yield of 50 to 75%, began to be produced using the sulfite method in the second half of the 20th century, and the next one, with a wood yield of approx. 65 to 85% in the interwar period (Szwarcsztajn 1957; Olszewski and Surewicz 1960; Surewicz 1990).

In the early 1960s, refiner pulp (RMP), began to be produced, with a wood yield of 94 to 96%. The next stage of development of refiner pulps was the development of a method for producing TMP, CMP, and CTMP pulps. As for the former first pulps, their production began in 1963 with a wood yield of approximately 91 to 94% and with a significantly higher share of long-fibre fraction and strength potential than SGW, but with a 60% higher electrical energy consumption (1900 to 2200 kWh/t *vs.* 1200 to 1400 kWh/t). The inclusion of chemical treatment in the production of RMP and TMP pulps led to obtaining CMP and CTMP pulps with a yield of approximately 86 to 90% and 90 to 92%, which through supplementation of technology with bleaching resulted in obtaining BCTMP pulp (Bleached Chemi-Thermo Mechanical Pulp) (Bøhmer 1986; Surewicz 1990; Surma-Ślusarska and Mróz 1995).

The youngest method of the pulp industry is APMP chemimechanical pulp produced by defibration of wood chips treated with a hydrogen peroxide solution in an alkaline environment, which allows the pulp to achieve a brightness of up to 80% after its production from chips (Bohn and Sferanzza 1989; Xu and Sabourin 1999).

Comparatively large technological and technical progress has also been achieved in the aspect of preparing wood for processing into papermaking pulps, washing these pulps after the pulping process, regenerating pulping chemicals, and cleaning them.

INDUSTRIAL PRODUCTION OF WRITING SUBSTRATES AND DIVERSIFICATION OF ITS PRODUCTION

Theoretically, it is possible to imagine the industrial production of stone or limestone tablets for writing purposes at any time in human history. However, without the use of machinery, this would be difficult, even using softer limestone. Given the potential for damage during production, such substrates would have to be of considerable thickness, making them quite heavy and therefore impractical. The development of their production would be also unfavorably influenced by the limited scope of diversifying their use because of their weight, susceptibility to breakage, stiffness, inability to absorb liquids, inability to create other products from them through bending, and their complete opacity.

Unlike stone tablets, the potential for producing clay tablets in large quantities should be assessed as significant, given that they can be formed from properly kneaded clay and fired similarly to clay vessels, which is a relatively simple process. However, the potential for diversifying the use of clay tablets should be assessed as low, for the same reasons as in the case of stone tablets.

The potential for producing writing materials from palm leaves in large quantities is significant in warm climates. Their manufacturing technology was relatively simple. In addition to using these leaves as writing materials, their traditional use was in food service. However, only recently has there been scientific interest in standardizing their use as a sustainable packaging solution. For example, Myuma and Alexander (2023) state that palm leaves have a robust structure and a tensile strength of 30.5 MPa, which enables the creation of relatively sturdy woven containers and adequate tensile strength for food packaging applications. Furthermore, palm leaves have high water-moisture resistance making them potentially suitable for wet or moist food products. However, this material has limitations in terms of the possibility of manufacturing a wide range of products using it resulting from the need for a specific packaging production method (the necessity of using the technique of braiding strips of palm leaves) and the inability to produce thinner, absorbent, thicker, and stiffer materials with a large surface area, or translucent materials.

Assessing the writing materials discussed in the subsection “Tree bark, wooden and metal tablets, ivory, porcelain, animal skins, canvas, and silk” in terms of their industrial production potential, it can be concluded that such production is impossible in the case of ivory and tree bark due to the difficulty of obtaining the former and the oval shape and fragility of the bark. The industrial production potential of porcelain, sheet metal, wax, leather, and canvas is greater, but these materials are difficult to obtain and necessary for other applications. Limitations on the possibility of diversifying the use of these substrates also result from its:

- High specific gravity (sheet metal, porcelain).

- The technologically difficult process of forming rigid three-dimensional products from them (metal sheet, wood) and the low possibility of forming such products (leather, fabric).
- The inability to quickly absorb water (sheet metal, wood, porcelain, wax).
- High opacity and the inability to reduce it (sheet metal, wood, porcelain).

The potential for producing large quantities of Egyptian papyrus (EP) can be described as limited due to the territorial limitation of occurrence of the papyrus plant and the impossibility of fully mechanization of EP production. The potential for diversifying its uses beyond writing and painting to create occasional items (event cards, graduation certificates, gifts for tourists) (Naiel *et al.* 2024) also appears to be limited due to its stiffness, hardness, density, fragility when folded, low absorbency, yellowish color, and sensitivity to moisture (Bausch *et al.* 2022).

The specific nature of the raw material used for production of parchment (obtained from the slaughter of animals), the considerable labor involved in its processing, and the inconvenience of the production process (biological animal material) did not, and still does not allow for the production of parchment in large quantities. It has certain beneficial properties, such as opacity, the ability to be partially transparent, smoothness, and lack of cracking when folded. Even today, these properties are utilized because parchment is still produced and for making "quality" documents, book binding, crafting membranes for drum and musical instruments, and lampshades (Fuchs 2018). However, it cannot be given the high stiffness, water absorption, and the ability to dissolve and form other products from its base substance, which are required for diversifying its applications.

Amate, huun, and tapa writing substrates, apart from being used to record information, were also used to make clothes (so-called bark fabric), furniture coverings, and wall hangings (Fig. 11A) (Loebner 1972) dyed by dyeing or stenciling. Their production technology was relatively simple, allowing for production in significant quantities, for example, 480,000 pieces per year, which demonstrates the hallmarks of mass production. However, the availability of the raw material, *i.e.*, the bark of the above-mentioned plants, may be a factor that limits production. Amate paper is still produced in Mexico, but rather as one of many paper crafts in this country. Wholesale buyers have attempted to expand its use beyond the traditional use of creating products, such as lampshades, notebooks, furniture covers, wallpaper, fancy stationery, envelopes, book separators, invitation cards, and cut-out figures, but about half of all amate paper production is still sold to painters (Sandstrom and Sandstrom 2012). The possibilities of further diversification of the use of this material are probably limited to this type of product due to the stiffness of technical bast fibres, high surface roughness of products made using these fibres, and the inability to increase its transparency, and density.

The possibilities for mass production of "rice" paper and waste silk fibre paper were limited in the former case by the precision-required production method and the limited availability of the raw material and its low strength properties, and in the latter case low papermaking potential of silk fibres. These factors also prevented the diversification of the use of these "rice" paper for purposes other than writing or artistic purposes and production of silk paper.

In the case of papers and paperboards soon after their invention, the potential for significant diversification was recognized by using the for production of processed papermaking products used for purposes other than writing. Examples include everyday products and home furnishings from China and Japan, such as hats, sheets, curtains, lamps, screens, waxed umbrellas (Fig. 44A), fans (Fig. 44B), toys (Fig. 44C), clothes (*e.g.*, kimonos), walls, and doors of houses (Lindberg 1960; Tsien 1974; Antoszewska-Moneta 1997; Alamy 2024; Web-Japan 2024).

This was made possible by paper's properties, such as its ability to be colored and coated, its semi-translucency, its low specific weight, the ability to fold the paper without cracking, and the ability to cutting it and gluing. However, during the period of paper production from rags in Europe, its use for purposes other than writing was limited due to the scarcity of this raw material and the low paper production.

Fig. 44. Chinese paper products: (A) umbrella (China 2025), (B) lantern (postage stamp), and a kite (C) (Web-Japan 2024) (author's computer drawings based on references cited)

However, the situation changed radically after 1850. By mechanization, both thin and thick paper (paperboard) could be produced in still increasing quantities. This production carried out in integrated pulp and paper mills (Fig. 45) over time started to exceed its demand for printing and writing purposes. The required quantities of paper and board with standardized parameters, as well as papermaking pulps, could be purchased for increasingly diverse applications.

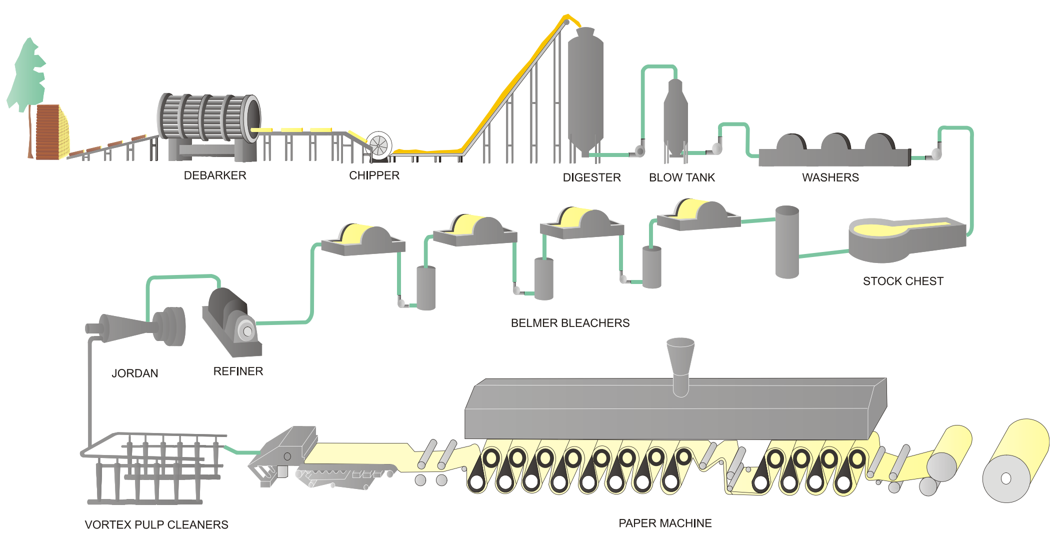


Fig. 45. Diagram of the pulp and paper plant with integrated production of unbleached pulp and packaging and paperboard paper – an integrated pulp and paper mill (author's drawing)

This enabled the use of the previously mentioned paper properties, as well as others, such as the ability to:

- Bind minerals and special substances inside it and coat it with these substances to improve its performance properties and give it new functional properties, improve surface aesthetics, or provide it with identifying features.
- Increase its transparency.
- Densify its structure through pressing, leading to increased stiffness.
- "Cast" paper products using 3D vacuum screen molds.
- Produce multi-layer products with cushioning properties.
- Partially or completely dissolve paper pulp fibers, and regenerate their base substance, *i.e.*, cellulose.
- Produce very thin papers, crease them, and thus obtain soft absorbent products.

The mentioned processes enabled the production of various types of printing papers, absorbent tissue papers, industrial and technical papers, various types of paperboards, and paper products for household and technical applications, materials, such as films and fibers in specially designed papermaking or chemical processing plants with a high degree of specialization.

Examples of Products and Processed Products that Contributed Significantly to the Development of Pulp and Paper Industry

Printing, writing, drawing, and wrapping papers

The mechanization of paper production has enabled the introduction of innovative technical solutions, the application of which in industry has resulted in the production of many types of papers for printing, writing, drawing, and packaging.

Printing papers are designed to be printed using specific printing techniques. Furthermore, they are also adapted to their lifespan and the quality of the image they are intended to convey. Because these requirements vary significantly between papers, printing papers exhibit significant differences in thickness, surface type, fibre type, filler content, sizing, surface finish, whiteness, porosity, and strength. Furthermore, writing and drawing papers differ from printing papers in their ability to absorb ink and paints. Examples of printing, writing, and drawing papers and their applications are shown in Figs. 46A through 46F, respectively (author's work, Figs. 46C through 46F based on Weyerhaeuser 1964).

As for the packaging papers, in the second half of the 19th century, the following papers were produced: *brown* coarse wrapping paper, *middle paper* used for making the centre layer of pasteboard, *paster* for covering the pasteboard, *shop paper*, which was white and machine glazed, *skip* used to line crates, and *bottle wrapping paper,* a special tissue paper. These papers were used as sheets or in the form of *counter reels* (Twede 2005).

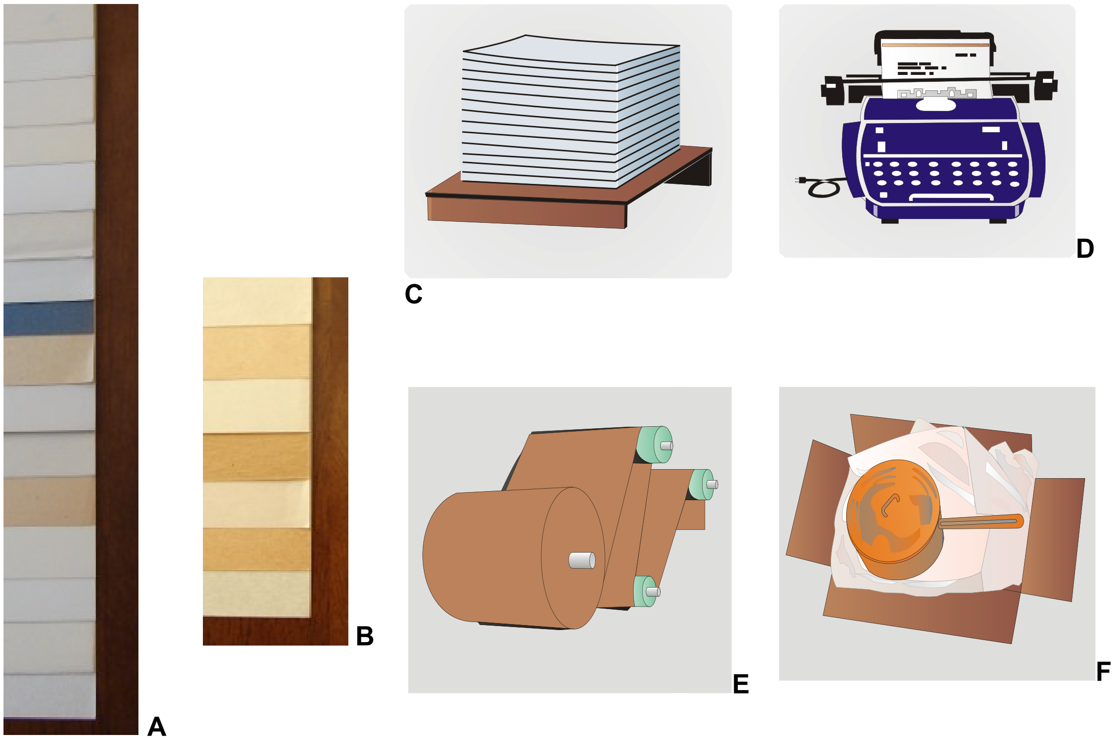


Fig. 46. A: Printing and writing papers (p) (starting from the bottom): coated halftone p., book p., draughting p., offset p., newsprint p., label p., fancy p., gravure p., advertisement p., writing p., bible p., glazed p., music p., art p., banknote p., cartograph p.;
B: Packaging papers: white kraft p., rope brown p., cover for paperboard p., sack p., white bag p., thin wrapping p., wrapping p.; C: A stack of papers ready for printing;
D: Filling a sheet of paper with text, evenly arranged and standardized in size and font type, using a typewriter; E: The production of wrapping kraft p.;
F: Using white thin wrapping p. to protect the pot in the box during transport

An early reference to using wrapping paper is in the first English patent pertaining to papermaking, granted to Charles Hildeyard in 1665 for "the way and art of making blew paper used by sugar-bakers and others." Books that failed to sell in London in the 1600s were sold as wrapping paper to grocers and apothecaries. This change of use was possible because books were stocked in sheet form, folded, but uncut and unbound until they were purchased (Twede 2005).

Examples of modern wrapping papers are shown in Fig. 46B. These include white kraft paper, rope brown paper, cover paper for paperboard, sack paper, white bag paper, thin wrapping paper, and wrapping paper. Wrapping papers are also named based on the type of pulp used in their production. Therefore, they are called recycled wrapping paper, straw wrapping paper, chemical pulp–mechanical wood pulp wrapping paper, and chemical pulp-recycled pulp wrapping paper.

Industrial and Technical Papers

This group includes papers used to produce numerous industrial products and technical papers for special applications. Many examples of these papers are shown in Fig. 47A through 47C.

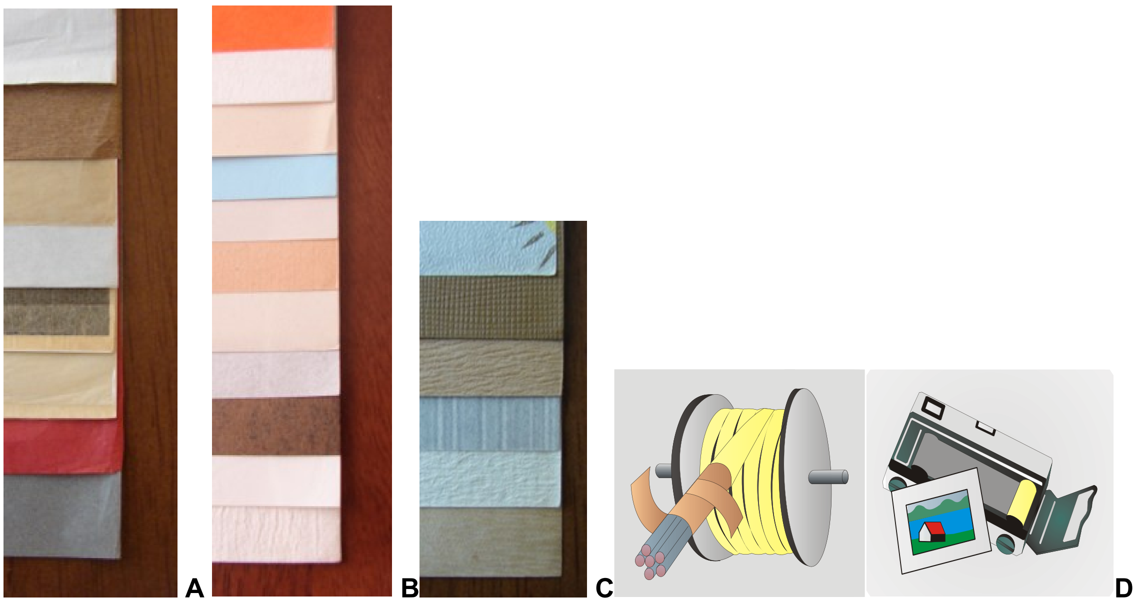


Fig. 47. Different types of industrial, technical, and special papers (p) produced by the papermaking industry (author's photos); A: Industrial and technical papers, thin papers (going from bottom to top): envelope lining tissue (t), carbon base red (t), capacitor (t), tracing (t), paraffine base (t), insulating winding (t), brown cigarette (t), and white cigarette (t); B: Industrial and technical papers, normal thickness papers: filter p., papeterie p., asphalt p., overlay laminate p., envelope p., hanging base p., protective p., core-sheets paper for laminates, decalcomania p., cotton–containing absorbent p., and oiled p.; C: Industrial and technical papers, normal thickness papers: wood veneer p., tablecloth p., cover p., crepe p., embossed p., and ornamental p.; D: Example of use of insulating winding p. (left) and photo p. (right)

Paperboards

There are probably over 100 types of paperboard produced today. In the English-Polish paper dictionary (Robowski *et al*. 1993), the entry for paperboard takes up 13 columns, each of which presents about 40 types of paperboards, mainly solid paperboards.

As for the solid paperboards, they can be divided into single-ply paperboards produced similarly to paper; glued paperboards (pasted paperboards), obtained by gluing two or more layers of single-layer paperboards in glue machines; and multi-layer paperboards, produced from several layers of fibre entanglement (felts).

Depending on the quality of the final product, solid paperboards can be made from wastepaper pulps, mechanical pulps, and kraft or sulphite pulps. Better quality solid paperboards, such as hard pack paperboard for cigarettes and medicines, graphic end-use paperboard, general packaging paperboard, and polymer–coated paperboard for food packaging, were made initially from the latter group of pulps, *e.g.*, semi-bleached and fully bleached kraft pulps. Such pulps give a very good product quality but make them expensive. Another drawback of such paperboard is its too low stiffness. The solution to this problem was to produce this type of paperboard as a three-layer product in which the middle layer was made of CTMP pulp (Engman *et al*. 1989).

Examples of different types of paperboards are shown in Fig. 48 A through D.

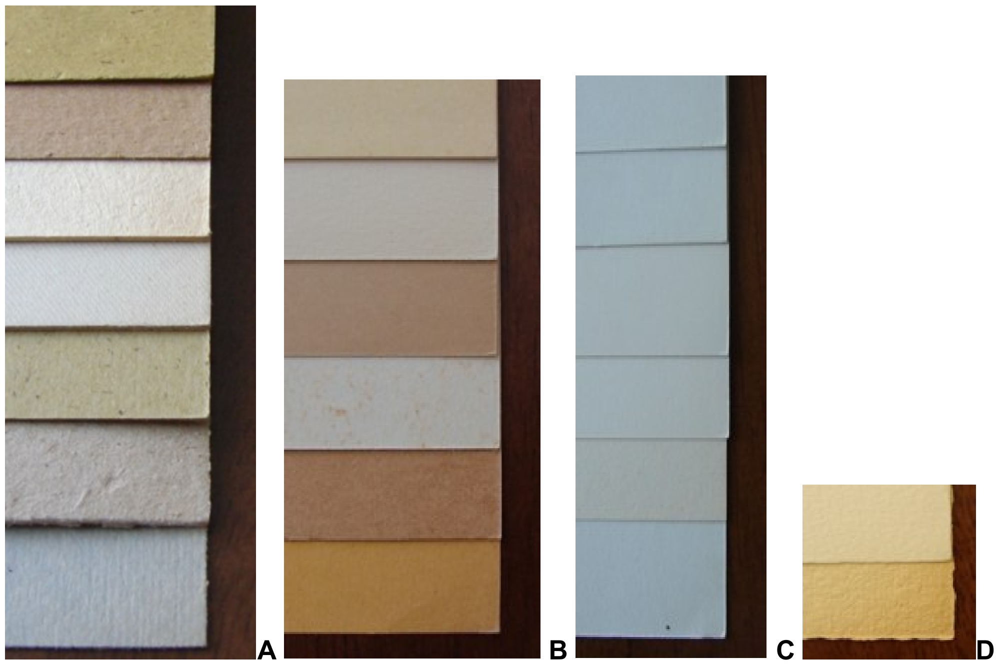


Fig. 48. Different types of paperboards (pb) (author's photo). A – simple types of pb (starting from the bottom of photos): chipboard, container pb, pb made from a mixture of different pulps (in German Mischpappe), cover pb, binder pb, imitation leatherboard, and straw pb;
B – Ticket pb, manila pb, pb for cups, label pb, photopaperboard, posting Bristol;
C – Bristol pb, postcard pb, ivory pb, coated pb, playing-cards pb, offset pb;
D – Copper-plate pb, aquarelle pb

Payment Products

Money and securities

The first paper money (the Chinese name ch'ao) appeared in China around 1010 to substitute for heavy metallic coins (Tsien 1974; Guan *et al.* 2024) (Fig. 49A). They have been named *jiaozi*, *qianyin*, *guanzi, huizi*, *zhongtongchao*, *zhiyuanchao*, and *zhizhengchao.* After 1356, paper money was rejected by the people and driven out of circulation (Guan *et al*. 2024).

Information about the possibility of using paper money reached Europe in the accounts of European travelers returning from China in the 13th century (*e.g.*, Marco Polo), but it was not until the 17th century that paper money was introduced into circulation in Sweden. The first banknotes, called treasury tickets (Fig. 49B), were printed also in Poland for a short time (during the Kościuszko Uprising) in 1794 (Dąbrowski 1995).

Over time, the form of paper money has evolved, and paper money replaced coins made of precious metals, which would have required enormous quantities to meet the growing demand for money in a given country with increasing numbers of people. The use of paper in money production stemmed from its ability to be adequately protected against counterfeiting, *e.g.*, by adding a watermark, using specific fibres, or very complex printing (Fig. 49C). Paper also proved to be a suitable material for issuing securities such as stocks, deposits, bonds, bills of exchange, and others (Fig. 49D).

Fig. 49. One of the first Chinese banknotes, first Polish paper money (author's computer drawing based on Bankier 2015), postage stamps showing development of banknotes in Ivory Coast Republik and examples of using paper for securities (Fig. 50D) (author's photo)

Postage Stamps

A postage stamp is usually described as a tiny piece of paper that is usually rectangular in shape with serrated edges and a white border, with a colourful photograph or diagram and one sticky surface. Less frequently, stamps come in other geometric shapes, such as circular, triangular, and pentagonal, or even irregular shapes. Thanks to improvements in printing techniques, nowadays, it is possible to include very complex drawings on stamps making them difficult to counterfeit and having high artistic value (Rajosoorya 2020).

Fig. 50. The first English (A) (Wikipedia13 2024) and Polish (B) postage stamps (Kupietz 2025) (author's computer paintings based on references cited)

Until the mid-19th century, the fee for postal items was borne by the recipient depending on the distance. The amount of this fee was set by the postmaster. As for international items, the fee up to the border was borne by the sender, and from the border by the addressee. The situation was changed by Rowland Hill, who in 1837 proposed that in England the fee should be borne by the sender. Thanks to his suggestions, in 1840 England introduced the first postage stamp, the so-called Penny Black (Fig. 50A), printed on paper with a watermark, which showed the head of the young Queen of England Victoria decorated with a background with a pattern that was difficult to counterfeit. On 1 July 1845 another country issued its first postage stamp, which was the Basel Dove, with a value of 2½-rappen. The stamp was printed in black, crimson, and blue and was the first tricolour stamp in the world.

On January 1, 1860, the first Polish postage stamp was introduced, depicting a two-headed Russian eagle against a shield (Marchlewska-Szrajerowa 1960; Reid 1984) (Fig. 50B). The introduction of postage stamps revolutionized the postal service, making letter writing accessible and affordable to all. Apart from that, stamps have become a powerful means of communicating an idea or depicting a chronicle of a history through depicting different stories, immortalizing people, events, buildings, and objects of discovery, *etc.* (Rayasoorya 2020).

Reading Products

Books

One of the most important processed papermaking products created thanks to the invention of writing and printing was the book. The invention of this type of product stemmed from the need to have a product for storing facts, knowledge, images, and artistic achievements of stable value in the form of words and drawings. This required not only appropriate material but also a large surface area for writing longer texts. It was precisely the capability offered by the book, distinguishing it from official documents, bills, and letters, which were intended for recording short texts of quickly passing value.

Fig. 51. (A) Gold sheets of golden book with text (Wikipedia14 2024), and (B) a fragment of column of text on page from the *Codex Sinaiticus* (Wikipedia15 2024) (author's drawings based on references cited), and (C) postage stamp showing *Alleppo Codex*

Taking this characteristic of the book as a criterion, one can consider papyrus scrolls (a type of unrolled book), palm leaves, wooden tablets, and metal tablets fastened together with string, leather straps, or metal wire as forms of the book [(*e.g.*, the six paged The Golden Etruscan Orphic Book, dated 660 BC or Pyrgi Gold Tablets, *ca*. 500 BC, Fig. 51A (Insight 2003; Ivanković 2023; Wikipedia14 2024)]. However nowadays, everyone associates a book with a product consisting of paper pages written with text, connected in a way that allows them to be viewed by turning them over and secured with a cover.

The first form of such a book was a notebook composed of several sheets of papyrus or parchment folded in half, which became common in the mid-1st century BC. These notebooks then evolved into products containing many more such sheets sewn together, called *codex*, analogous to several wooden tablets bound together, allowing for the storage of larger literary works. Parchment *codices* began to dominate Greek literature as early as the 4th century AD and replaced EP scrolls and EP *codices* in the 6th and 7th centuries (Muszkowski 1947; Meleczyńska 1974; Gamble 1995). They were easier to handle and archive and could contain a greater volume of information than books with pages made of palm leaves, woody tablets, and EG scrolls.

Other advantages of *codices* were that they made it easier to find the information you needed and were more durable because of greater resistance to weather conditions and greater resistance to tearing at the stitching site than EG codices. The examples of very well-known parchment codices are the *Codex Sinaiticus* (Fig. 51B), the *Codex Vaticanus Graecus* from the 4th century AD containing a manuscript of the New Testament, and the *Alleppo Codex* containing the text of the Old Testament (Fig. 51C; Gamble 1995; Nongbri 2022; Patil 2024; Wikipedia15 2024).

Fig. 52. *Diamond Sutra* (A) (Bookfact 2025), postage stamp showing Gutenberg and his Bible (B), and a serial book from a contemporary publishing house (C) (Węgłowski and Przeździecka 1979) (author's computer drawings based on references cited)

The first printed paper book (even though it is a scroll made of 7 pages glued together) is the so-called *Diamond Sutra*, made in China in 868 using fonts made by the woodcut technique (Surewicz 1994a; Helman-Ważny 2011) (Fig. 52A). After 1501, printed paper books (the best example of which is the J. G. Gutenberg Bible, Fig. 52B) began to quickly replace the handwritten codices. This period falls within the era in the history of European culture known as the Renaissance in which the book finally takes shape as a printed book, *i.e.*, the same as a modern book (Fig. 52C) (Dahl 1965; Bieńkowska and Chamerska 1987).

A breakthrough in the mass-published books production was the invention of machine production (Fig. 53A) of 16-page folders (*i.e.*, 8 card folds, the so-called printing sheet) and joining them together by gluing and sewing (Fig. 53B) using gauze or textile tape as a connecting element (Fig. 53C) (Wijato and Zalewski 1958).

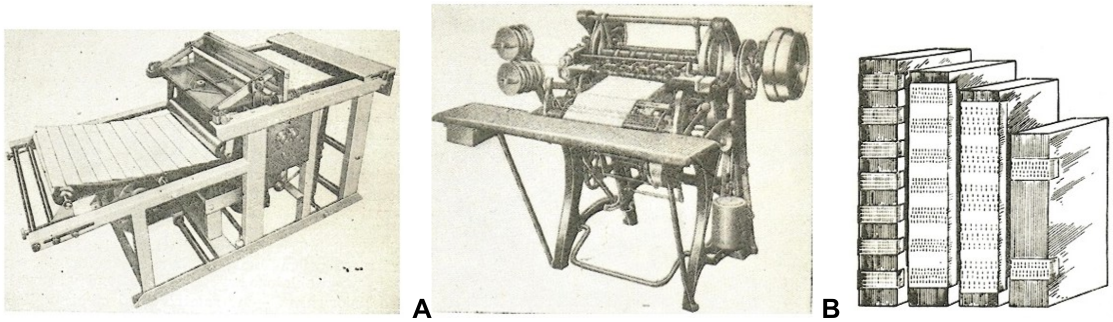


Fig. 53. Machine for making folders of book (A), machine for stitching folders of book, and stitched folders of books (Wijato and Zalewski 1958)

Newspapers

A newspaper is a type of ongoing publication, published daily or at least twice a week, that provides readers with important information and opinions of journalists, analysts, subject matter experts, scientists, and technicians. It is one of the main sources of knowledge dissemination on various issues, aiming to provide readers with in-depth insight into those issues and assist them in making decisions (Sutar 2007; Khalid and Ahmed 2014; Wikipedia16 2024).

Fig. 54. The *Relation* newspaper (Wikipedia16) (A), *Aviso* newspaper (Wikipedia17) (B), *Merkuriusz Polski* newspaper (C) (Wikipedia17 2024), and contemporary daily and magazine newspapers (D) (author's drawing)

The prototype of newspapers was newsletters published by the Fugger family in Germany in the 15th and 16th centuries containing reports of business and other affairs circulated within the Fugger Organization (Sutar 2007). The first newspapers included the *Relation aller fürnemmen und gedenckwürdigen Historien* (documented since 1605), printed in Strasbourg (Fig. 54A) and the *Aviso Relation oder Zeitung* in Wolfenbüttel from 1609 (Fig. 54B) (Schröder 2001; Hillgärtner 2021; Wikipedia17 2024; Wikipedia18 2024). The first daily newspaper in the world was probably *Einkommende Zeitungen*, published for the first time in 1650 in Leipzig (from 1734, *Leipziger Zeitugen*), published until 1921 (Hillgärtner 2021, Wikipedia19 2024). Other early newspapers were the English *The Corante, or, News from Italy, Germany, Hungary, Spain and France*, published for the first time in 1621 (Haig 2025) and the French *La Gazette* from 1631 (Miller 1932; Espejo 2011; Wikipedia18 2024). The first periodical newspaper published in Poland and in Polish was *Merkuriusz Polski Ordynaryjny* (Fig. 54C), issued in 1661 (Fig. 54D) (Sarnecki 1961; Wikipedia16).

For many years, until the invention of groundwood, newspapers were published on paper made from rags. Newsprint with the addition of 25% groundwood began to be produced in 1857. In 1898, sulfite pulp began to be used to produce this paper, and it took a long time before groundwood completely replaced rag pulp. In 1931, newsprint was already made from 50% sulfite pulp and 50% groundwood. Over time, this proportion changed to 80% groundwood and 20% sulfite pulp, and then to 20% semi-bleached kraft pulp. Currently, groundwood in newsprint formulations is replaced by thermomechanical pulp (TMP), and the amount of pulp in the pulp mixture used to make newsprint depends on the speed of the paper machines (Marchlewska-Szrajerowa 1961; Sarnecki 1961) (Fig. 53D).

Since the beginning of their existence, newspapers have played important political, economic, and cultural roles, such as (Khalid and Ahmed 2014):

- A source of information about world, national, and local events and analyses of this information.
- A forum for expressing views and public discussion.
- A creator of public awareness and social attitudes.
- An instrument of education, contributing to the development of human resources and economic growth.
- A provider of various forms of entertainment.

The importance of newspapers has significantly decreased with the development of competition in the transmission of information and entertainment from radio, television, and currently the Internet and smartphones, along with a related decrease in the number of advertisers. For this reason, newspapers have changed over the last few decades. One of these trends was the increase in the amount of visual content in newspapers and the attractiveness of such content. Another is a departure from the presentation of mainly news and a transition to a more discursive form, *i.e.*, comments and opinions. A move in the opposite direction was to retreat from reporting mainly political, economic, and social issues in favour of trivial, personalized (*e.g.*, feminine, lifestyle), sensational, scandalous, entertaining, and even salacious news to satisfy the needs of the readers and attract them. Another salvation for newspapers was to use the niche of local content in the media space, as well as offering readers the possibility of purchasing their digital version as well (Steel and Conboy 2008; Khalid and Ahmed 2014).

Hygienic Products

Tissue and hygienic papers

This group of papermaking products has a wide range of types and application, such as facial tissues, kitchen towels, hand towels, sanitary towels, napkins, toilet tissues, and wipes (Fig. 55A). This diverse assortment of tissue products is commercialized in two market segments, *i.e.*, Away from Home (AFH) professional or institutional segments and At Home (AH) domestic and consumer tissue segments (De Assis *et al*. 2018). Tissue products can be further divided into Economy and Value products (EV), Premium products (PR), and Ultra products (UL) that differ in content of high-quality fibres, recycled fibres, and low-quality fibres. Compared to EV products, PR products contain much more high-quality fibers. The best quality represents UL products, which have a minimum amount of recycled fibres and usually 2 or 3 plies, and are made using more advanced technologies, *e.g.*, through-air drying (TAD) (Zou 2017).

These products are most often made from very low-grammage tissue paper (*e.g.*, 14 to 21 g/m^2) (Bytomski *et al*. 2024) (Fig. 55B and 55C). Therefore, special manufacturing techniques and equipment must be used for its production. Light Dry Creped (LDC) is the most conventional technology. The main differences between an LDC machine and a conventional, non-sanitary paper machine are the shorter length, Yankee cylinder dryer, and creping processes, which increase the bulk, absorbency, softness, and stretch of tissue papers. Different types of pulps can be used for tissue production, *i.e.*, virgin, recycled, chemical, mechanical, semi-mechanical, bleached, unbleached, hardwood, softwood, and non-wood. Softwood fibres are used in tissue and hygienic papers because they provide strength to them, while hardwood pulps are primarily used for their ability to provide bulk, softness, and a velvet surface feel (De Assis *et al*. 2018). The best quality (soft) of creped tissue paper is obtained from bleached sulfite pulp from spruce wood (Sawicki 1952; Myślińska 1962) and northern bleached softwood kraft pulps because, due to their low coarseness-to-length ratio, they enable the attainment of strength without the loss of softness that comes with other softwood pulps (De Asis *et al*. 2018).

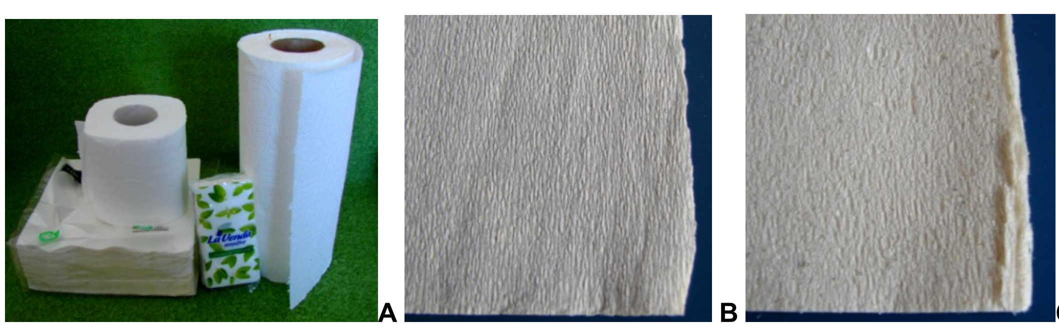


Fig. 55. Various types of paper products made of creped tissue paper (A) (Ad7 1960-1969), cellulose wadding (B) called lignin in Poland, and creped cellulose tissue paper (C) (author's photo)

Packaging Papermaking Products and Packaging Processed Papermaking Products

The earliest forms of packaging materials were leaves, hollowed-out tree limbs, leathers, reed baskets, and earthenware vessels as containers. As civilization developed, more complex packaging was developed to meet specific needs, such as glass and ceramic vessels, those made from paper-like materials, and then from metal, paper, paperboard, and plastic. Of the above-mentioned packaging, those made of paper and paperboard are particularly important because they are much lighter than the others, are made from renewable raw materials in a natural way, are easier to obtain, and are also cheaper (Raheem 2012). These include e.g., wrapping paper, paper bags, boxes made of solid paperboards and corrugated paperboards, and paper containers cylindrical in shape. The function of these packaging is to protect the product it is in from contamination, prevent it from being damaged, surround it, facilitate its transportation, attract the attention of customers in the market, and facilitate sales (Polat 2022).

Folding paperboard boxes

Folding paperboard boxes (Fig. 56A-D) are believed to have been first used in China as packaging for fine teas. In Europe, the first paperboard set-up boxes were first produced in the 1700s in Germany and England by hand, and sometimes at home. An example may be recognized as the first American paperboard box, *i.e.*, paperboard box for gauze cap of Quaker Minister Rebeca Jones dated on 1785 (Bettendorf 1946). However, making a paperboard box in this way was a labor-intensive craft and has a major disadvantage, *i.e.*, after it is set-up by the box maker, it cannot be shipped to the packer/filler in a flattened form. As set-up boxes became popular, inventors looked for a more efficient way of their production, which led to the invention of folding paperboard boxes (Twede 2005). Commercial paperboard box production dates back to 1817 and is sometimes attributed to the company M. Treverton & Son, which was the paperboard box, not the corrugated paperboard box. In turn, the inventor of manually pre-cut paperboard or paperboard folding box was Scot R. Gair (Fig. 56E) (1879) who developed a mechanized method for die-cutting and scoring folding cartons in a single stroke (Twede 2005).

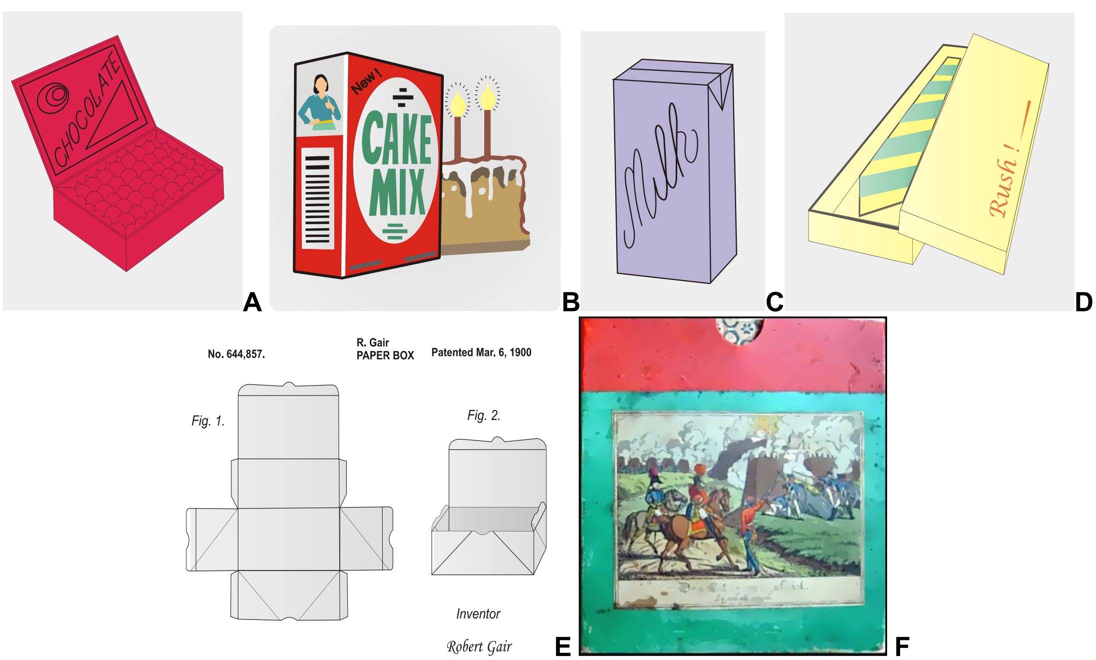


Fig. 56. Contemporary solid paperboard boxes (A-D) (author's drawings based on Weyerhaeuser 1964), R. Gair's folded paperboard box (author's drawing based on Polkowski 2024) (E), and first use of such a box to pack a board game (author's computer painting based on Dennis 2020) (F)

An example of the first documented use of a solid paperboard box to pack market goods was most likely the packaging of the board game "The Game of Besieging" in 1817 in Germany (Fig. 56F) (Dennis 2020).

Later examples of using folding paperboard boxes are packing cosmetics, cigarettes, bottled products, crackers, and cereals which enabled moving away from measuring out a quantity of product by the retailer from large packages, *e.g.*, barrels or bulk bins, and enabled the products to be displayed on shelves, which led to the period of "consumer packaging" (Twede 2005).

Paper bags

Paper bags are typically processed papermaking products from the section: *packaging* and group: *paper packaging* (Wijato and Zalewski 1958). The first form of paper bag (Fig. 57A) can be considered as the paper twisted into a cone to hold loose items. Before the 1800s and in the first part of the 1800s, paper grocers' bags were also made by gluing paper by hand by a storekeeper who cut, folded, and pasted sheets of paper, making containers into which purchases could be loaded for carrying. The first machine for mass production of paper bags was invented in 1852 by Francis Wolle (Fig. 57B), a teacher from Pennsylvania (USA). Wolle and his brother patented this machine and founded the Union Paper Bag Company, which was the first paper bag manufacturer (Petroski 2003; Twede 2005; Wikipedia20 2024; Wikipedia21 2024).

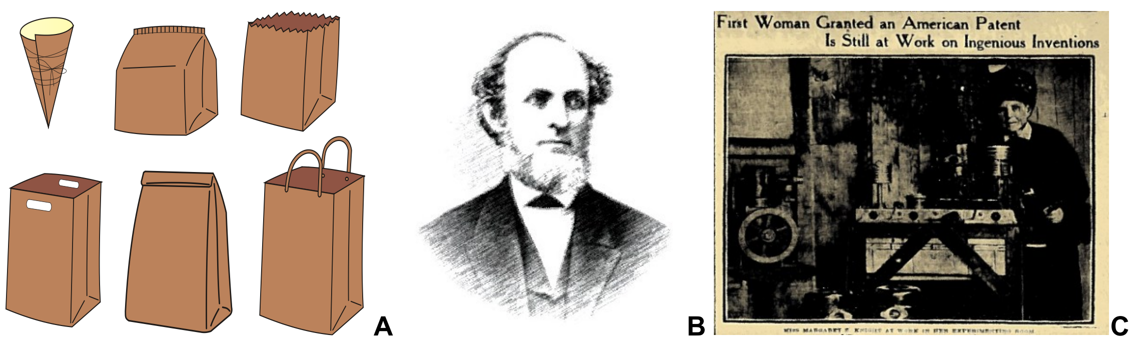


Fig. 57. Contemporary paper bags (A) (author's drawing based on IIIIline 2025), inventors of paper bag making machines, F. Wolle (B) (author's computer drawing based on Wikipedia20 2024), and Margaret E. Knight (C) (photo refreshed by author based on original from Wikipedia21)

In 1853, James Baldwin, a papermaker from England, received a patent for a device for making square-bottomed paper bags. In 1870, inventor Margaret Eloise Knight (Fig. 57C) designed a machine that produced flat-bottomed paper bags that could hold more than envelope-type paper bags. Knight's machine helped to automate the bag-folding process; in turn, the flat-bottom design provided a sturdier structure to carry items in the bag (Fig. 58A) (Bolanča *et al*. 2018).

In 1883, Charles Stilwell patented a machine that produced paper bags with a square bottom and pleated sides, which made them easier to fold and store (so-called Self-Opening-Sack bags) (Fig. 58B). In 1912, Walter Deubener of Saint Paul, Minnesota (USA), proposed adding string ears to paper bags to make it easier to carry purchases in them (Wikipedia22 2024; Splash Packaging 2025).

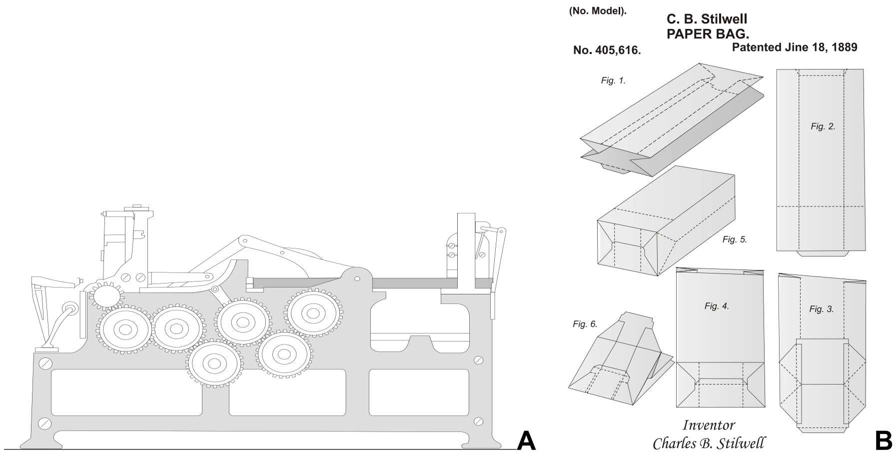


Fig. 58. M. E. Knight bag machine (A) and a bag with a square bottom and pleated sides developed by C. B. Stilwell in 1889 (B) (author's drawing based on Pavlus 2025 and Chipbruce 2015, respectively)

Corrugated paperboard and boxes made of this type of paperboard

Corrugated paper (ruffled, fluted, pleated) (Fig. 59A) was invented in England in 1856 by Edward Allen and Edward Healey for keeping the shape of tall hats (Fig. 59B) (Goettsch 1975; Twede 2005; How Life Unfolds 2024). It was initially formed on the same kind of fluted irons to make ruffled collars (Fig. 59C).

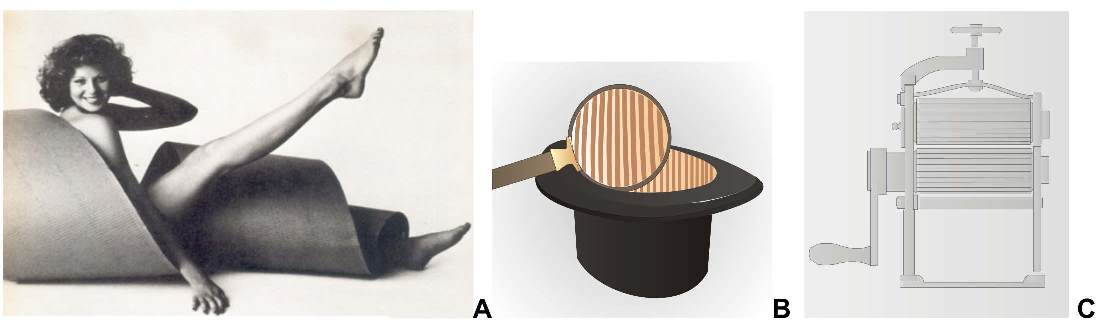


Fig. 59. Ad of fluting paper (author's scan of photograph of an unknown author found in waste paper) (A), stiffening of a hat cylinder with a paperboard flute (B) (author's drawing based on Fefco 2024), a device for fluting fabrics adapted to produce a paper flute (C) (author's drawing based on Cabell 1878)

However, the patent for the use of fluted paper to secure goods in transport was obtained fifteen years later (1871) by Albert L. Jones in the patent office in Washington (USA). It was a textured cushioning material intended for wrapping glass bottles to protect against breakage. The disadvantage of this type of paper product was, however, its susceptibility to permanent deformation. It was not until 1874 that Oliver Long came up with the idea of covering one or both sides of the corrugated paper layer with flat paper to protect it and prevent stretching, and thus corrugated paperboard was created. Ultimately, however, the patent for corrugated paperboard was taken over by Robert H. Thompson, Henry D. Norris, and Robert Gair. Corrugated paperboard was initially manufactured by hand, using corrugators used for ruffles for fabrics intended for window curtains, shirt cuffs, and dress collars, *etc.* (Bettendorf 1946; Goettsch 1975; Twede 2005).

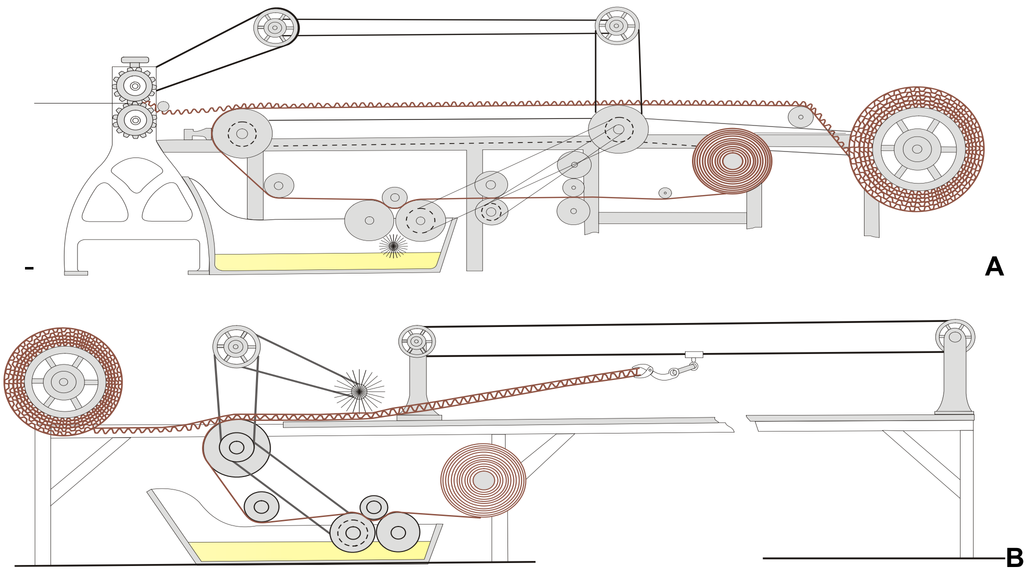


Fig. 60. Drawing of R. H. Thompson's machines for producing two-layer (A) and three-layer (B) corrugated paperboard from a patent from 1882 (author's drawings based on Bettendorf 1946 and Goettsch 1975)

The efficiency of this method was low. However, machines were also introduced into industrial practice gradually over the course of about 30 years after corrugated paperboard was invented. This allowed for the mechanized production of two-layer (Fig. 60A) and three-layer (Fig. 60B) corrugated paperboard with an increasing production speed and improved properties of such paperboard (Fig. 61A to 61C).

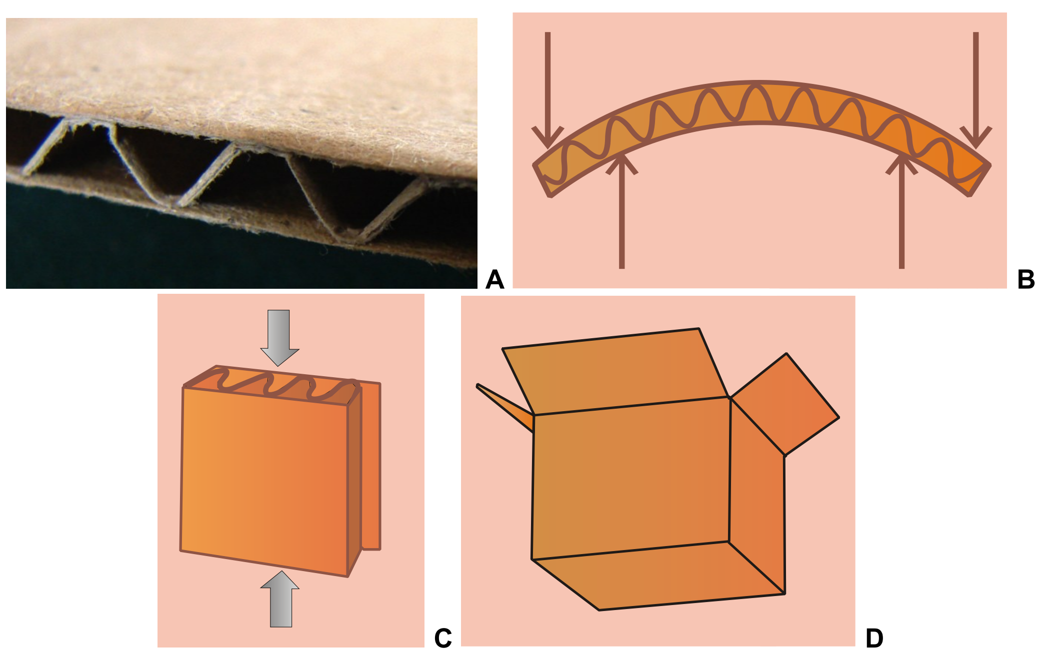


Fig. 61. Structure of three-layer corrugated paperboard (A) (author's photo), its most important properties [resistance to bending (B) and crushing (C)], and the most important processed product of corrugated paperboard – paperboard box (D) (author's drawings)

This was facilitated by the great interest of producers of various goods looking for cheaper and lighter packaging that would better protect the goods than the wooden boxes commonly used at that time (Bil 1972; Goettsch 1975). The first corrugated paperboard box (Fig. 61D) was produced in the USA in 1894 by Henry Norris and Robert Thompson and was intended for packaging goods sent by post (Bettendorf 1946). The widespread adoption of corrugated fibreboard shipping containers required a great deal of political negotiations and technical development. This required time but led to the state that an increased number of types of goods began to be shipped in fibreboard boxes due to their light weight and low cost.

Products for Serving Food, Packaging It, and Taking It Away

The use of papermaking packaging materials and products for food packaging dates back to the 17th century. However, the increased use of these products started in the later part of the 19th century and in the 20th century (Marsh and Bugusu 2007). These products include, most often bags, trays, cups, takeaway containers, boxes, cylindrical packaging, and Tetra Pak-type containers (Fig. 62A to 62C).

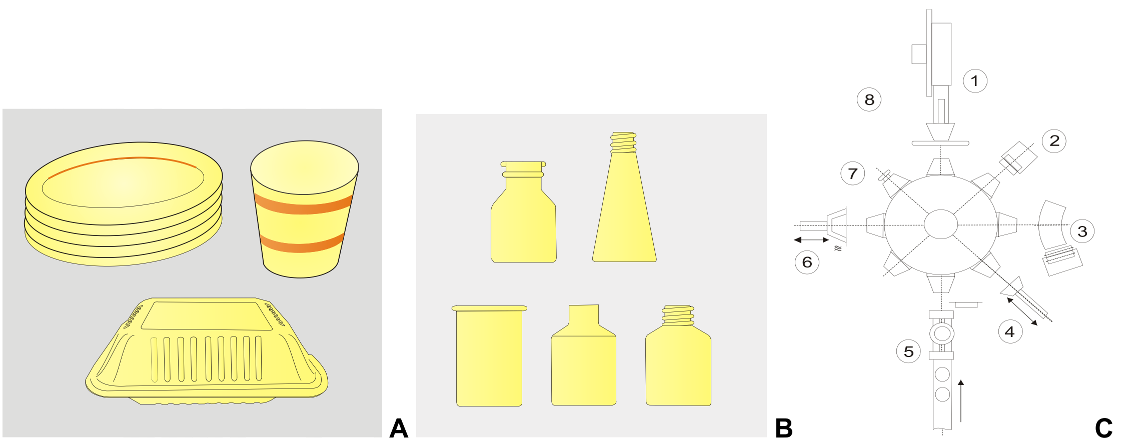


Fig. 62. Disposable tableware: paperboard plate, cup, and packing case with a hinged lid (A) (Logipackhoreca 2024), reusable paper containers: bottles, jars, and cans (B) (Wijato and Zalewskki 1958), and diagram of the operation of the machine for producing paper cups (Wijato and Zalewski 1958) (author's drawing based on references cited)

In the second half of the 20th century, most of this packaging was manufactured mainly from synthetic polymer materials. This created a huge challenge in terms of waste management and pollution. It is widely known that natural decomposition of such materials in the environment takes several hundred to a thousand years, sometimes releasing toxic particles and substances in the process. Therefore, now, paper or pulp alternatives to plastic products for serving food, taking it away, and packaging are more and more often used. *Paper bags* in gastronomy are used to pack fries, hamburgers, hot dogs, and casseroles. They can be rectangular or triangular in shape, have or have no side fold, and have the form of satchel or strip window bags. They are made of artificial parchment, paraffin, or laminated papers (Budziński 1994; Raheem 2012; Deshwal *et al*. 2019).

Advantages of *boxes* for packaging for food products in comparison to bags include better stiffness of the walls, a shape that allows good use of storage and transport space, and their printing. These types of boxes are divided into open (*e.g.*, for packing cakes, cookies), flap (*e.g.*, for hamburgers, pizza), drawer, lid, and folding types. Several types of paperboard are used for their production, *i.e.*, linerboard, foodboard, folding boxboard, chipboard, baseboard, whiteboard, and solidboard (Deshwal *et al*. 2019). *Paper trays* are used for short-term storage of food products intended for immediate consumption. They are produced by extruding paperboard. Paperboard for making trays can be laminated with one-sided chalk paper, offset paper, parchment paper, or aluminum foil. Paperboard trays can be flat, semi-deep, deep, square, oval, round, and specially shaped. Such trays have raised and profiled (*e.g.*, bent, wavy) corners and edges, respectively, to dispose of excess material in these places. The bottoms of trays are often convex or profiled to improve their stiffness. The earliest attempts of the paperboard-based liquid food packaging date back to 1915, when John Wormer of Ohio (USA) patented a 'paper bottle,' which he referred to as *Pure-Pak*. It was a predecessor of contemporary *Tetra Pak* packaging consisting of six layers, including polyethylene and paper, with paper contributing approximately 70% of the total packaging material used in a single pouch (Deshwal *et al*. 2019). *Paperboard cups* are used for packaging of drinks, ice creams, jellies, fries, and other various foods. The method of their production in the 1950s is shown in Fig. 62B. It consisted of eight operations. These were (Wijato and Zalewski 1958; Budziński 1994) the following:

(1) Cutting out the bottom.
(2) Coating the bottom with glue.
(3) Coating the fold of the jacket of the cap tube with glue and gluing it to the other end of the fold to create a cap tube .
(4) Folding the jacket from the bottom and gluing the inner bottom to the cap tube.
(5) Cutting out the outer bottom while simultaneously coating it with glue and gluing it to the inner bottom.
(6) Curing the glue.
(7) Pressing the bottom onto the jacket with electrical heating and folding the upper edge of the cup.
(8) Ejecting the finished vessel from the device.

Products Made from Papermaking Pulps Subjected to Advanced Mechanical or Chemical Processing

Acid vegetable parchment (AVP), parchment paper, and tracing paper

The first factory of AVP (Fig. 65A), also called *papyrine*, was launched in 1860 in London. The founder of this factory was Warren de la Rue, who used W. E. Gaine's patent from 1853 to produce such kind of paper on an industrial scale. The method of AVP was changed from periodic to continuous in 1884 by the Austrian R. Fritsch (Machlewska-Szrajerowa 1960).

This parchment is fabricated from high-quality paper initially immersed in a concentrated sulfuric acid (H_2SO_4) bath with a density of 52 to 55° Baumé (67.8 to 70% H_2SO_4) for 2.5 to 3.0 seconds at a temperature of 10 to 15°C. It is subsequently processed through a mangle that squeezes out excess of acid from it, next a rinsing bath, a neutralizing bath, a rinsing tank again, a glycerine bath, and finally through drying cylinders and smoothing rollers. In these processes, first the outer layers of the fibres dissolve, transforming them into a semi-transparent mass (called by some authors amyloid), which fuses the fibres together, and then the cellulose precipitates into a granular substance (today it is known that this is poorly crystallized cellulose II), which fills the pores in the paper and thus takes the form similar to animal parchment (Sawicki 1952; Wojciechowski 1952; Baranow and Dobrowolski 1955; Cartier *et al*. 1994). A certain role in obtaining AVP properties may also be played by the abstracting of the water molecules by H_2SO_4 in the linkages between the fibres, and fibrils, which densifies the paper structure (Clark 1984). AVP is completely impermeable to fats but not completely resistant to water and has little resistance to elevated temperatures (above 60 °C). The problem with this kind of material is its low recyclability, which can be increased by pre-treating it with enzymatic preparations from the cellulase group (Cartier *et al.* 1994).

One American advertising brochure for vegetable parchment listed as many as 179 applications for *papyrine*. The most important of them was its use as a packaging material in various branches of the food industry and in trade. After World War II, a significant part of *papyrine's* applications was taken over by foils and packaging made of synthetic polymers (Machlewska-Szrajerowa 1960). Similar products to AVP are parchment paper and tracing paper (Figs. 63C and 63D).

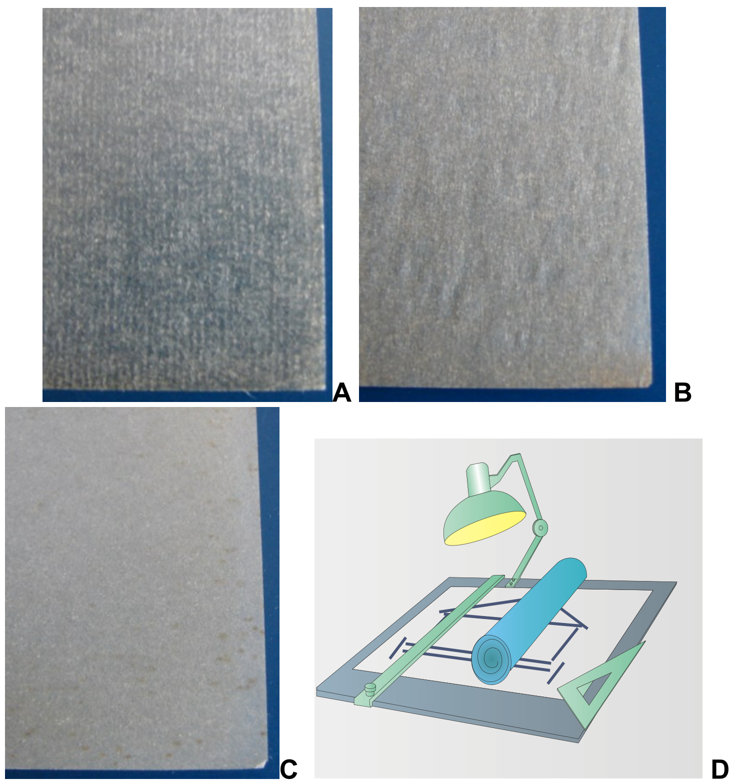


Fig. 63. Vegetable parchment (A), parchment paper (B), technical tracing paper (C), and its use (D) (author's drawing based on Weyerhaeuser 1964)

Parchment paper is obtained using pulp, which is beaten to 85 °SR-freeness. It is smooth and matte, with a compact, cohesive structure, semi-transparent, with increased resistance to water and fat penetration, but much lower than AVP; high tensile strength, but lower resistance to bending and tearing. Such paper was widely used for packaging products that needed to be protected from aroma loss, drying, and moisture, and for wrapping fatty products. Tracing paper, on the other hand, was made of spruce-fir parchment pulp, which allows for obtaining the most transparent paper with even transparency, characterised by high cohesion and stiffness (C) (De Tournelle 1953; Wijato and Zalewski 1958). The pulp used to make tracing paper is even more finely beaten than that used to make parchment paper.

Parchment paper and tracing paper are created thanks to the ability of paper pulp fibers to create an increasingly transparent layer with increasing density, achieved through increased fiber flexibility, fibrillation, flattening, and refinement which after calender pressing creates the semi-transparent paper structure thanks to the absence of light-reflecting or light-absorbing faces in or on the fibers. However, such pulp properties require long beating times and slow down the production process of parchment and tracing paper due to the high freeness of pulp. Therefore, Vaurio in 1960 investigated the possibilities of achieving transparency in paper using various liquids. Recently published articles on transparentizing papers indicate that interest in these papers is growing. For instance, Zhu *et al*. (2013), reports that transparent papers can potentially replace plastic screens of electronic devices just as plastic has replaced glass in this kind of products.

Form-moulded pulp products (FMPPs)

The process of creating different FMPPs started after M. L. Keyes received a patent for the technology in 1890 and developed a machine prototype for generating FMPPs in industrial conditions. It entails depositing water-dispersed fibres on a sieve with the product's shape and then drying them. A characteristic feature of form moulding (FM) is the ability to form a whole three-dimensional product without the need first to produce paperboard and its processing by cutting or rolling and finally gluing. After the World War I, Joseph Coyle created the first industrial machine for making egg trays. The use of this process to create packaging for other products that needed to be protected (fruits, light bulbs, *etc.*) was patented in 1920. Thus, the use of form-moulded pulp products gradually increased between 1920 and 1940. Many FMPPs, including *soft molded* FMPPs (Fig. 64A) (eggs trays, flower pots, bread trays, bottle coverings for fine wine, food trays, and plates) and *hard molded* FMPPs (Fig. 64B) (television and radio cabinets, furniture parts, moulded luggage, various panels, gear covers, bucket seats, globes, bathtubs, buckets, and bowls) were made using the FM process in the 1950s and 1960s (Didone *et al.* 2017; Debnath *et al.* 2022; Danielewicz 2025).

However, the extensive usage of thermoplastic polymers and plastic foam packing for industrial product components at the start of the 1970s hindered the development of the manufacture of FMPPs (Didone *et al*. 2017; Debnath *et al*. 2022; Rane and Thakker 2023; Danielewicz 2025).

Fig. 64. Soft FMPPs A), examples of application of *hard* moulded FMPPs (B), and *thermoformed* moulded FMPP (author's drawing based on Emry and Emry 1966) and (B) (author's photos and drawing)

The manufacture of FMPPs is currently undergoing a period of rapid technological and technical progress. The need for biodegradable packaging and storage solutions is rising because of the global shift towards sustainable and eco-friendly packaging options. The value of papermaking products made worldwide using the FM method increased from 8,537 million dollars in 2020 to 10,219 million dollars in 2024, according to statistical data computed using the CAGR. Positive data is also reported by the pulp moulding machine market. According to FMI (2025), the market is anticipated to grow at a compound annual growth rate (CAGR) of 3.7% and reach a valuation of USD 1.1 billion between 2023 and 2033.

The observed increase in FMPPs production is due to the growing interest in using packaging materials made from renewable raw materials, which can be easily recycled multiple times or incinerated without releasing fossil carbon into the atmosphere. This is supported by (Debnath *et al*. 2022, Danielewicz 2025):

- The development of machines for the production of conventional FMPPs in terms of production speed, compactness, multifunctionality, automation, the ability to produce several types of FMPPs in a single device, low energy consumption, and small factory space requirements.
- Availability of machinery for the production of thermoformed or injection molded FMPPs enabling the achievement of a high-quality, smooth surface for these products, enabling full-color graphics to be printed on both sides, dimensional accuracy, low product draft angles, and greater product depth.
- Return to the production of FMPPs such as bottles and other containers using newly developed, modern methods.
- Development of eco-friendly chemicals for imparting barrier properties to FMPPs to make them resistant to the penetration of water, oil, and fats, such as polylactide acid (PLA), nanocrystalline cellulose (CNC), cellulose nanofibril (CNF), thermoplastic starch (TPS), chitosan, alginates, whey protein isolates (WPI), isolated soy proteins (SP), zein corn protein, prolamin protein, carboxymethyl cellulose, crosslinked cellulose, and often composites of these substances.

Rayon, cellophane, nitrocellulose, celluloid, and cellulose acetate

Rayon (RA), also called viscose, is a semi-synthetic fibre, made through the treatment of a special kind of pulp produced in the pulp and paper industry (solubilizing cellulose using alkali and carbon disulfide and pushing it through the spinneret holes into a coagulation bath). English chemist Charles Frederic Cross and his collaborators, Edward John Bevan and Clayton Beadle, patented the method of production of RA in 1894. RA is a versatile fibre and is widely claimed to have almost the same comfort properties as natural fibres. It can imitate the feel and texture of silk (it is also called artificial silk), wool, cotton, and linen. The fibres are easily dyed in a wide range of colours. RA fabrics are soft, smooth, cool, comfortable, and highly absorbent, but they do not always insulate body heat, making them ideal for use in hot and humid climates, although also making their “hand” feel cool and sometimes almost slimy to the touch (Fig. 65A) (Keist 2009, Wikipedia23 2025).

A cellulose product having far much better transparency than AVP and parchment paper is cellophane (Figs. 65B and C) from the words “cellulose” and “diaphane” (meaning transparent”). It was invented by Jacquees Edwin Brandenberger in Switzerland in 1911. Cellophane is a clear and transparent or coloured rustling cellulose film of thickness used as a glossy transparent wrap for high-end candies, cosmetics, moisture barrier wrap for food products, tobacco, and other luxury goods (Fig. 65D). It is obtained similarly to rayon, *i.e.*, by derivatization of dissolving pulp with carbon disulfide and sodium hydroxide to an alkali-soluble sodium cellulose xanthate, dissolution of it in dilute sodium, passing the solution through a slotted nozzle into a coagulation bath (Charles 1963; Paunonen 2013). It contains about 12% of a plasticizer, *i.e.*, glycerine. This material is flammable and loses strength under the influence of water. The thickness of contemporary cellophane can be, *e.g.*, 30 μm, permeability 0.11 kg/(m^2·h·bar), tensile strength 40 MPa, and elongation at break 65% (Makarov *et al*. 2022). Cellophane is biodegradable, but non-biodegradable synthetic films have pushed this product off the market due to the inconvenience of producing cellophane. Recently, however, less burdensome methods of producing cellulose films are proposed using the ability to dissolve cellulose in alkali/urea/H_2O mixture with a weight ratio of 4.6:15:80.4% and N-methylmorpholine-N-oxide (NMMO) technology (Twede 2005; Paunonen 2013; Wikipedia24 2024,). Moisture proofing of cellophane is obtained by coating it with an extremely thin film of nitrocellulose or synthetic polymer (Sid *et al.* 2021). The disadvantage of cellophane is that it has a dead fold (*i.e.*, once folded, it cannot be folded back) and it is susceptible to scratches. This makes it difficult to use in mechanical food packaging. At one point in the past, its price was higher than films made from synthetic polymers, such as, *e.g*., polyvinyl chloride. These factors meant that cellophane's range of applications began to significantly decline over time. However now, cellophane production is increasing, driven by demand for sustainable packaging and stricter environmental regulations (DataInsight 2025).

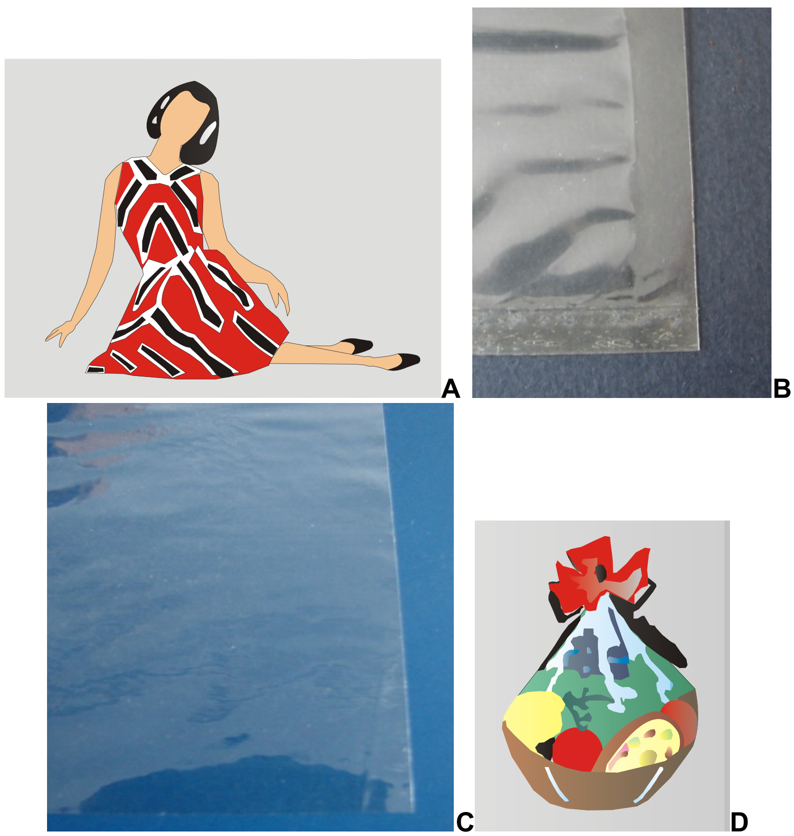


Fig. 65. Dress made of viscose textile (A), viscose foil as the imitation of glass (B), cellophane film (C), and one of its applications (D) (drawings and photo author's work in the last case based Weyerhaeuser 1964)

Nitrocellulose (NC) is obtained by exposing fibrous cellulose to the mixture nitric and sulfuric acids and water under appropriate conditions, which transforms it into a form containing hydroxyl groups substituted with nitro groups of the formula $[C_6H_7O_2(ONO_2)_3]_n$ (cellulose trinitrate). The maximum nitrogen content in NC is theoretically 14.14% (usually less in practice). NC appears as a white, fibrous, cotton-like material with an ether-like odor. The negative features of NC are its sensitivity to moisture and limited biodegradability. With the appropriate nitrogen content, it has proven to be a flammable and strong explosive material (Fig. 66A). Over time, its usage broadened to encompass various sectors, such as the production of lacquers, varnishes (Fig. 66B), putty, paints, and filtration membranes, due to its properties such as excellent film-forming ability and good mechanical strength (John *et al.* 2024; Wikipedia25 2024; Tufan and Özelb 2024).

If nitrocellulose is mixed with camphor in a ratio of 70%:30%, a transparent, plastic-like material called celluloid is obtained, which dissolves in organic solvents. The technology of celluloid production was patented by brothers John Hyatt and Isaiah Hyatt in 1870. In the past, celluloid was widely used in the haberdashery industry, in the production of toys, film tapes, photographic films, motion picture reels (Figs. 66C and 66D), fountain pens, and many other everyday items (*e.g.*, ping-pong balls). Today, this material is rarely used. It is being withdrawn from production and replaced by less flammable materials, including acetyl celluloid, which is a thermoplastic material created with a base of cellulose acetate and is non-flammable (Charles 1963; Wikipedia25 2024, Tufan and Özelb 2024).

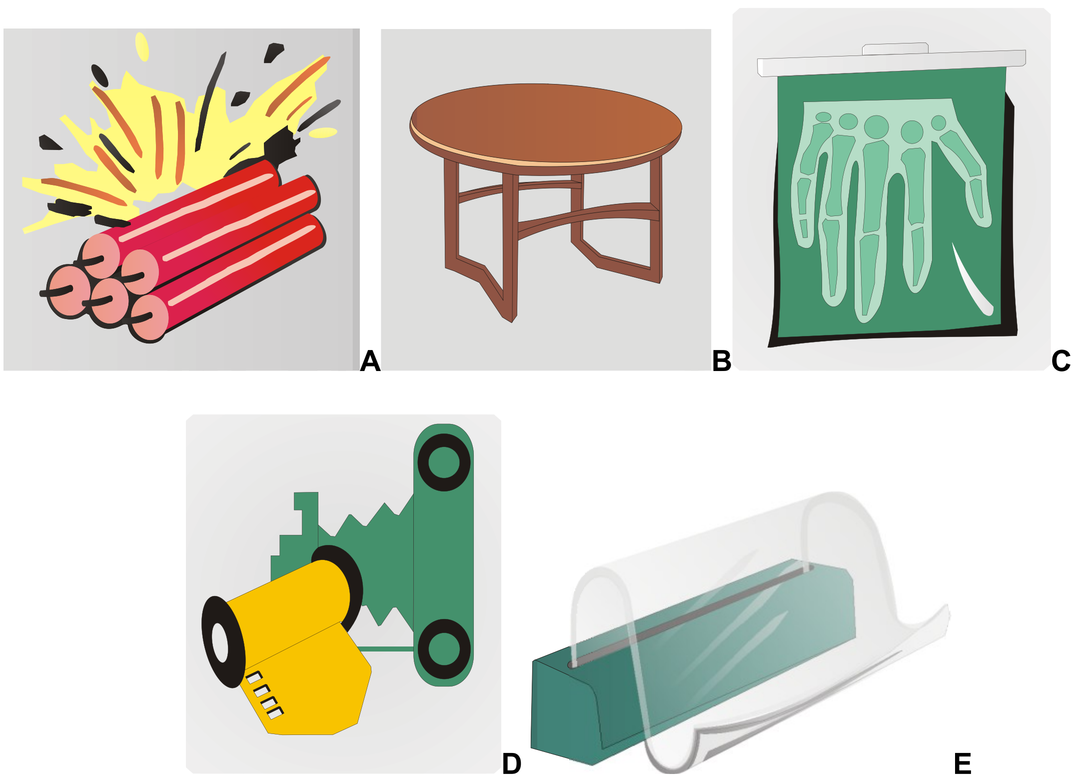


Fig. 66. First applications of nitrocellulose: explosives (A), an example of the use of nitrocellulose varnish - varnishing furniture surfaces (B), nitrocellulose-based X-ray film (C) and photographic film (D), and cellulose acetate film (E) (author's drawings based on Weyerhauser 1964)

However, today, when environmental consciousness and the depletion of natural resources, like fossil fuels, minerals, natural gas, *etc.*, has shifted our attention towards renewable products, interest in expanding the use of nitrocellulose seems to be growing (John *et al.* 2024).

The advantage of cellulose is the possibility of modifying it with various reagents. Therefore, it possible to create a film-forming substance based on cellulose that shows significantly lower susceptibility to ignition than a nitrocellulose films. This substance is cellulose acetate (CA). CA is manufactured by the reaction of plant cellulose with acetic anhydride and acetic acid.

The inventors who are considered to have introduced CA to industrial production were Camille Dreyfus and his younger brother Henri, who in Switzerland from 1904 to 1910 managed to organize the production of safety motion picture reels for the cinema industry and varnish for the aviation industry, and in subsequent years the yarn for the textile industry (Bianchini and Alves 2003, Wikipedia26 2025). Today, CA is still produced and is used to manufacture *e.g.*, disposable cutlery and cups for hot drinks, wrapping fresh and baked goods (it can sustain high temperatures) (Fig. 66E), as well as other products, including those made from blends of this biopolymer and other substances (Sid *et al.* 2021).

Barrier Products

Asphalted felt paper

Asphalted felt paper revolutionized roofing technology after its invention. This invention became useful especially in rural areas where cereal straw was commonly used as roofing. It was manufactured for the first time in the 1950s, and it is extensively used today due to its unique qualities. Its main function is to provide a protective layer that resists outdoor conditions (*i.e.*, as a weather resistive barrier, WRB) and maintains the integrity of the internal structures of a building, protecting them against moisture either on roofs or walls (Bustos *et al*. 2017).

Felt paper (Fig. 67A) was used to produce asphalted felt paper, a cheap material used to cover wooden roofs of buildings to this day. In the classic method of obtaining it, it was made from jute, cotton, wool rags, textile waste, and appropriately selected waste paper (up to 50%) because it requires a long fibre. In the process of producing rag pulp, one can distinguish the dry and wet preparation of rags. Rags were delivered to the plant in bales. These bales were untied and passed to the bale breaker. From the breaker, layers of rags fell onto a stretching conveyor and then a sorting conveyor, on which the rags were cleaned of impurities (rubber, stones, metal). The rags were then cut in cutters equipped with magnets and dusted in an air stream equipped with a cyclone. The cleaned rags were then passed to the wet stream, where they were subjected to defibration in a disc mill and then reground in Hollander beaters to standardize the fibre length and then sent for forming into single-layer felt on a flat screen machine.

After obtaining the felt paper, it was initially impregnated with oil-like tar and then sprinkled with sand of appropriate grain size. Later, unbleached kraft paper was used to produce felt paper. This was then impregnated with oxidized asphalt, with the addition of a bituminous mixture containing SBS (styrene-butadiene-styrene) elastomers or APP (atactic polypropylene) plastomers. Such impregnation improved the durability of the asphalt felt paper, their range of use, and their resistance to low and high temperatures (Fig. 67B). For this reason, the roofing felt had to be absorbent, fluffy, and soft (Sawicki 1952; Fuławka 1966; Należyty and Skoczylas 1972; Winczakiewicz 1976; Bustos *et al*. 2017; Dachy 2023).


A B

Fig. 67. Raw roofing paperboard (A) and a modern example of the use of asphalted roofing felt in Poland (B) (author's photos)

Asphalted-felt paper has several advantages, such as relatively good resistance to damage and temperature fluctuations, water impermeability, low cost, and a history of successful use, making it a good material for securing roofs against rain and the foundations of houses against moisture. However, it was deficient in some aspects, *e.g.*, it had relatively low tearing resistance, and it is affected negatively by too long exposures to weather conditions (Bustos *et al.* 2017).

Construction Products

Pressboard

Pressboard (Fig. 68A) is a type of multi-layer, strongly pressed paper or paperboard with a thickness of about 0.2 to 50 mm, with high density (1.15 to 1.35 g/cm^3), abrasion and bending strength, and resistance to absorption. It was already made in 1900 (Twede 2005). To produce pressboard, cellulose kraft pulp from softwood, specially cleaned of all impurities, is used. This pulp is defibred in deionized water and milled to obtain good separation of fibres from each other, and is sent to the stage of forming paperboard structure of flat screen or round screen type paper machines producing reel or sheet type of paperboard (Krause 2012). The sheets or reels are then dried in periodic or continuous type drying presses at a pressure of 150 kg/cm^3 and more, and at a temperature of 120 to 140 °C.

In the literature on the subject other detailed issues of pressboard manufacturing technology are also discussed i.e., for example (Sawicki 1952; Wojciechowski 1952; Gzylewski and Winczakiewicz 1959; Gołębiewski 1960; Skubała 1968):

- The use of sulphur milk in the production of pressboard. The sulphur contained in this milk is melted during pressing in order to evenly distribute it between the fibres and gives the pressboard the properties of a good non-hygroscopic insulator.
- The use of calendaring and polishing of pressboard with agate stones to give them smoothness.
- Saturation of pressboard with solutions of synthetic resins or plastic masses or impregnation with rapeseed or castor oil with an admixture of sulfur dichloride to improve its properties.

Pressboard was/is used, for example, for (McLaughlin Paper Company 2025):

- Document storage and filing supplies (classification and file folders, organized and durable solution for document storage).
- Report covers (after decoration, professional-looking report covers).
- Packaging (secure and protective folding cartons).
- Durability and visual appeal tags and labels.
- Industrial applications (back panels for radios, televisions, and other electronic devices).


A


B

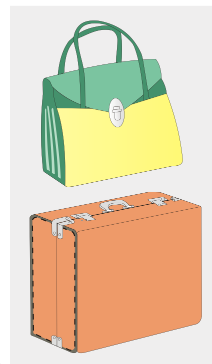

C

Fig. 68. Pressboard (A), "vulcanized" paperboard (B) and one of their applications (C), *i.e.*, to forming stiffen the walls of the woman's handbags and suitcases (author's photos and drawing)

"Vulcanized" paperboard (VB)

Vulcanized paperboard (Fig. 68B) is fully based on the renewable raw material cellulose and was first developed in the mid-19th century. It is made of absorbent and unsized special papers joined by a merging process into a homogenous material by adding a parchmentizing solution. Predominantly, a zinc chloride solution ($ZnCl_2$) is used for parchmentizing. During the process the crystalline structure of cellulose I is converted into cellulose II, which is an irreversible and pure physical process (Scholz *et al*. 2016).

The production of VB consists of passing a paperboard web through a concentrated zinc chloride solution in a special machine. After this process, the web is wound onto a forming cylinder to the desired thickness, creating a material similar to plastic laminate. This process is called vulcanization. Then, the obtained fibre web is removed from the cylinder, cut, rinsed from zinc chloride, dried, air-conditioned, and smoothed to give it greater flexibility. VB is produced in sheets 0.5 to 20 mm thick, characterised by high strength and elasticity, and a very smooth surface. It is resistant to fats and oils, is easy to machine, and wears out little. It can be stamped or embossed. Varnishing or paraffin treatment reduces the hygroscopicity of this material to a minimum. The density of VB reaches 1.1 to 1.5 g/cm^3, tensile strength 450 to 700 kPa/cm^2, elongation at break 6 to 10%, and hardness is 700 to 1200 kPa/cm^2. Due to its good insulating properties VB/VF has been used in electrical engineering to produce, *e.g.*, tubes and rollers, used to insulate electric wires. In mechanical engineering, it was used to manufacture various seals, brake elements, disks, plates, rings, handles, tool handles, and similar products. VB/VF was widely used also in the automotive, textile industries, as well to produce everyday products, such as bags, suitcases, and purses (Fig. 68C), embossed articles, buttons, and cap visors (Sawicki 1952; Wojciechowski 1952; Fuławka 1966; Leman 1968). Studies have shown that zinc chlorine solution swells and fibrillates fibres, which increases the cellulose availability index and decreases its crystallinity index, promoting an increase in the density of the laminate made of paperboard sheets, the degree of its internal bonding, and the strength at break of VB in a dry state (Bliesner 1964).

With the development of plastics on the base of low-molecular raw materials, like mineral oil, vulcanized fibre was almost fully substituted in technical processes. Now there is a feeling of increased interest concerning VB as an alternative resource-saving material for industrial applications because of its good life cycle assessment, resource efficiency, and lightweight construction potential (ρ = 1.3 g/cm (Scholz *et al*. 2016).

Unconventional Products

One of the most unconventional paper products is *shifu* fabric (*shi*-paper, *fu*-fabric) produced in Japan and Nepal from endless yarn/thread obtained by twisting paper strips cut from a sheet of paper (Fig. 69A). Its invention probably originated from the desire to use cheaper fibrous raw materials than linen and silk to produce fabrics.

Fig. 69. A sheet of paper with cuts and a place where a strip was torn from the edge of the sheet, and a strip of paper after it was separated from the sheet (A) (author's drawing based on Witkowski 1991), a paper dress in a package from 1960s offered for sale on e-bay in 2025 (author's drawing based on based on Ebay1 2025) (B), the package of men's paper coverall for work in car workshops or on ships (author's drawing based on Ebay2 2025), and paper reinforced with a mesh of threads, *i.e.*, so-called paper cloth (D) (author's photo)

The greatest development of technique of making *shifu* occurred in the period from the mid-18th century to the mid-19th century (today *shifu* probably has only the status of artistic products). In Japan, the threads for making *shifu* were twisted from strips of special paper called *shifugami* (kozo, gampi, mitsumata), and in Nepal from paper – *lokta* made from *Daphne papyracea*. Clothing made of *shifu* fabric was light, warm, comfortable, and absorbent, both in warm and winter periods of the year. It could be impregnated with adhesives made from plants called *konnyaku* in Japan and washed. The disadvantage of this type of product was the difficult manufacturing technique (Witkowski 1991).

The use of paper as a substitute for products traditionally made using fabrics can also be considered unconventional but also innovative. Robowski (1968), and Bil in 1971 provided examples of the use of paper as textile-type materials such as curtains (curtains, drapes), bedding (sheets, pillowcases), clothing (dresses, work clothes) (Fig. 68B and C), and products for hospitals use (sheets, aprons, bed linen). However, for this type of application, paper has several disadvantages, including too low tear resistance, relatively high stiffness, a rustling effect, low strength when wet, and flammability. These inconveniences can be reduced, however, by, for example, gluing thin layers of paper, creping it, or reinforce it using chemicals, or thread mesh (Fig. 68 D).

Radzimski (1955) also mentions the possibility of purchasing paper raincoats in stationery stores in some countries. Such products have been made of wet-strength paper or paraffine-waxed paper.

Unconventional uses of paper certainly include its use in the production of balloons. The use of paper in the production of balloons took place in 1783, when the Montgolfier brothers demonstrated that a balloon made of paper impermeable to warm air was able to lift living creatures into the air (a rooster, a ram, and a duck) and stay there for 10 min. The Montgolfier brothers are also credited with inventing the paper parachute, which was tested in Avignon in 1779, with an animal as a passenger (Marchlewska 1960). As Marchlewska states, "We therefore owe the first flights to paper".

EPILOGUE

Writing substrates were invented out of the need to preserve and disseminate thoughts, images, sounds, knowledge, and to obtain the possibility of correspondence between people.

These materials have evolved strongly throughout human history from the immobile walls of caves and temples, through thick portable surfaces (clay tablets, boards, bark, and ivory), to relatively thinner but heavy surfaces (metal plates), although thin and light but inconvenient for writing as cloth, tapa, and tanned leather, to easier to write on but unstable and territorially limited Egyptian paper and expensive parchments, and finally to paper made of long-fibred (rags) pulp and then from medium-length-fibred wood pulps. Of great importance in the evolution of writing surfaces to paper as we know it today was the mechanization of its production (the invention of the stamping machine, the Hollander beater, and the paper machine), the invention of methods for producing fibrous intermediates for its production (*i.e.*, various papermaking pulps), paper sizing, and methods of finishing its surface which took place mainly in Europe.

These achievements, together with the use of pulps obtained from wood – an easily available and cheap fibrous raw material in many countries of the world – enabled the mass production of writing, printing, and packaging papers, as well as mass production of processed paper products, such as books, school notebooks, and newspapers, which played an important role in the development of human civilization.

In parallel, in the 15th century, it turned out that thick paper, later called paperboard or cardboard, could be used for the binding of books, which can be considered a certain form of book packaging, initiating later the use of this material in the production of many packaging made of this type of paperboard.

The search for new applications for papermaking pulps, papers, and solid paperboards (*i.e.*, new possibilities of diversifying the applications of these papermaking products) led to the invention of products and processed products (not only papermaking), such as: safety papers (banknotes, postage stamps), paper impermeable to air and grease (artificial parchment-like papers), paper semi-permeable to light (*e.g.*, technical tracing paper), thin crepe paper (hygienic tissue paper), paper bags, corrugated paper, corrugated paperboard and boxes made of such paperboard, solid construction paperboards (pressboard, vulcanized paperboard), insulating paperboard (asphalt roofing felt), cellophane, cellulose derivatives (nitrocellulose, acetylcellulose), products made of these derivatives (*e.g.*, explosives, celluloid, cellulose acetate film), and form-moulded pulp products. This type of diversification, which can be called *1st generation diversification* of pulps, papers and paperboards has enabled an increase in global paper production to approximately 400 million tonnes today.

Some of these applications, although very popular in the past, *e.g.*, vegetable parchment-type products, pressboard, vulcanized paperboard, cellophane, and several other well-known cellulose derivatives, and *moulded* FMPPs, have lost some of their importance in the second half of 20th century because of the spread of production of products made from synthetic polymers. During the same period, the paper industry began to feel the effects of the digitalization of information transmission and recording, resulting in a reduction in orders for printing and writing papers for paper mills. It seems reasonable, therefore, to return to the wider use of such kind of products, which could be manufactured by modern modified methods. Further diversification of the use of fibrous papermaking pulps, paper, and board is also important to create new, previously unmanufactured processed products using these papermaking materials, such as *e.g*., new cellulose derivatives (Heinze and Liebert 2001), cellulose fibre insulation (Lopez Hurtado *et al*. 2016), aerogels (Long *et al*. 2018), microfibryllated and nanoparticle celluloses (Ioelovich 2022), and others. This could significantly contribute to maintaining the production capacity of the papermaking industry. In the author's opinion, this process could be called the *2nd generation diversification* of use of pulps, papers, and paperboards. It is important that products of *2nd generation diversification* do not contain non-recyclable or non-biodegradable substances, that their production generates a lower potential for global warming, acidification and eutrophication of soil and waters, and that they can be used more than once to achieve the appropriate level of recyclability, biodegradation, and LCA indicators, which as the latest studies indicate are not yet at the appropriate level for contemporary papermaking products (Simantiris 2024; Dolci *et al*. 2025).

An important role in this process is the education to not only papermaking engineers but also engineers of other industries dealing with innovative products about the history of humanity's use of writing substrates, their evolution to paper, and the significant opportunities for diversification of the use of this basic product of the papermaking industry, in which this publication may be of significant assistance.

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