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# Comparative evaluation of sodium tripolyphosphate production technologies with the use of a complex quality method

**Zygmunt Kowalski[1], Agnieszka Makara[2*], Anna Henclik[1], Joanna Kulczycka[3], Marcin Cholewa[1]**

*[1]Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Wybickiego 7, 31-261 Kraków, Poland*
*[2]Faculty of Chemical Engineering and Technology, Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland*
*[3]AGH University of Science and Technology, Faculty of Management, Gramatyka 10, 30-067 Kraków, Poland*
*[*]Corresponding author: e-mail: agnieszka.makara@pk.edu.pl*

A technological quality method was used to compare two methods of sodium tripolyphosphate (STPP) production. The first method was the classic spray method (CM) and the second was a dry single-stage method (DSM). The assessment criteria were environmental, based on Life Cycle Assessment (LCA) evaluation and economic, based on production costs. The technological quality assessment of CM was 6.5% lower in comparison to DSM. LCA environmental analyses showed that the partial environmental quality of DSM was lower by only 4.4% compared to CM. Partial economic quality was lower by 10.3%, mainly due to the lower energy costs (on average 52%) for DSM. The advantage of the new DSM method is the technological progress achieved, mainly due to the application of new technology, design, and apparatus solutions; thus, the basic elements of the activities proposed in the methodology allow for cleaner STPP production.

**Keywords:** life cycle assessment, sodium tripolyphosphate, technological quality, environmental evaluation, economic evaluation.

## INTRODUCTION

Pentasodium triphosphate(V), $Na_5P_3O_{10}$, also called sodium tripolyphosphate (STPP), is a polyphosphate belonging to the group of inorganic condensed phosphates in which the phosphate groups are joined together linearly by oxygen bridges[1, 2]. STPP, due to its physicochemical properties, is widely used in the chemical industry, as well as in other industries. STPP is a basic filler in active household chemicals, i.e. washing agents and detergents. The content of fillers in detergents ranges from several to several dozen percent, and their use for these purposes results, among other things, in their sequestration properties, which lead to the formation water-soluble complexes of alkaline earth metals and heavy metals. The formation of STPP complexes with calcium and magnesium ions reduces the hardness of water and causes the secondary dissolution of sediments, while heavy metal bonding prevents the corrosion of components of washing equipment. More than 70% of the currently produced STPP is used for the production of cleaning agents[3–5]. STPP buffering properties improve the efficiency of detergents and regulate the acidity of foods. Condensed phosphates also have the ability to form complexes with proteins or pectins, which counteract food dehydration (the so-called protein effect). The formation of complexes with heavy metal ions inhibits the oxidation reaction, preventing the growth of microorganisms in the food. The use of STPP in the dairy, fat, and fruit and vegetable industries also results in the stabilization of water emulsions, fats, and proteins[1, 6]. STPP has been applied as a dispersing agent in ceramic processing and can also be used as an inexpensive plasticizer in cement-based materials[7–9]. STPP also has applications in the food industry as an additive to meat products[10], in seafood[11] and as a conservation agent in fruit juice or milk[6]. With an increase in the application of STPP in industry, the demand for this product has also increased. The global STPP market is expected to increase up to 8.1 billion USD in 2022. About 70% of the total demand for STPP has been recorded in Asia-Pacific, Europe, and Latin America[12].

In recent years, as a consequence of increased environmental awareness in consumers, issues related to the improvement the quality of technologies and environmental protection in the strategies of companies and international organizations have risen in importance. This study performed a comprehensive evaluation of two methods of STPP production[6, 13, 14]. The first method studied was the classic spray method (CM), commonly used for the production of STPP. The second was a dry single-stage method (DSM) developed and tested under laboratory conditions. The technological quality method was used to compare these methods. The assessment criteria were environmental, based on LCA evaluation and economic, based on production costs.

## MATERIALS AND METHODS

The method applied a comparative assessment of both analyzed methods of STPP production using a complex quality method to qualitatively characterize compared technologies. The aim here was to choose the better method. The assessment of the complex quality of technology comprises quality features ("n" could be any number). One resultant number can determine an entity characterized by numerous quality features[15, 16]. The complex quality (Q) is therefore a function of variable quality features:

$$Q = f(W_i) = f(W_1, W_2, ... W_n) \qquad (1)$$

where: Q is complex quality, $W_1$ … $W_n$ are variable quality features.

The assessment of technological quality comprised two steps of partial expert assessments: environmental hazards and the economics of enterprise[17]. In turn, the arithmetic sum of the environmental and economic assessments resulted in a value of the complex quality of the technology.

$$Q_T = Q_{EN} + Q_{EC} \quad (2)$$

where: $Q_T$ is technological quality, $Q_{EN}$ is partial environmental quality, $Q_{EC}$ is partial economic quality.

$$Q_{EN} = F / w_c \cdot a_j \text{ or } Q_{EC} = F / w_c \cdot a_j \quad (3)$$

where: F is the scoring of STPP production variants (points), $a_j$ is the degrees of validity, $w_c$ is the value of the criterion assessment. The value of the criterion assessment $w_c$ (1 point = ) was defined as 0.01 F maximum of the scoring of STPP production variants (points). Importance degree $a_j$ was arbitrarily assumed from values 1–4.

**Environmental analysis of STPP production with the LCA method: goal and the scope of the study**

LCA is a technique to assess environmental hazards by identifying and determining the amount of materials and energy used in the analyzed production and waste released into the environment. The impact of these processes is then assessed[18]. The use of LCA can be considered a standardized method[19, 20] for analyzing the environmental chains of products at different stages in their life cycle. All LCA stages include the extraction of the resources, their delivery to the factory, the manufacturing of the product, its use, treatment, and, after it is discarded, its reuse, recycling, or final disposal. Therefore, LCA enables the evaluation of the cumulative environmental impacts resulting from different stages in the product life cycle[18, 21, 22].

The environmental impact assessment was carried out using SimaPro software[23]. The LCA methodology used in this study followed the standards ISO 14040 and ISO 14044[19, 20]. LCA evaluations were performed using International Reference Life Cycle Data System (ILCD) 2011 Midpoint + v. 1.09[24, 25], the implementation of which proposes the feasible implementation of a combined midpoint/endpoint approach with 16 impact categories. It supports the correct use of the characterization factors for impact assessment, as recommended in the ILCD guidance document[25]. ILCD is representative of European conditions and the final result of the analysis is an eco-indicator, giving a value for its impact on the environment. The normalization coefficients used for the analysis were assumed according to the Product Environmental Footprint (PEF) guide[24]. Because of this, the ILCD weight coefficients, representative of European conditions, have not been weighted, in accordance with the recommendations of the PEF guide, and the weight indicator was assumed to be equal to 1. This means that all categories of environmental footprint impact are treated equally. It is important that, in the case of LCA comparative assessments, the difference between two subjective values becomes an objective value[25].

Life cycle analyses are also carried out for input product systems in which unit processes are created based on material and energy balances, containing elements of exchange directly with the environment (in this analysis: water intake from the river, dust and gas emissions) and those that have been processed by man and already have their impact on the environment and human health through the production, packaging, and transportation processes (in this analysis: phosphoric acid, sodium carbonate, pressured air, energy carriers). Further processing includes all processes that led to the acquisition of a given raw material/energy carrier. So, this study of STPP manufacturing used the cradle-to-gate system. The functional unit was defined as 1 t produced STPP, prepared for sale to the customer. The scope of the LCA and the system boundaries for the full comparative analysis are shown in Figure 1.

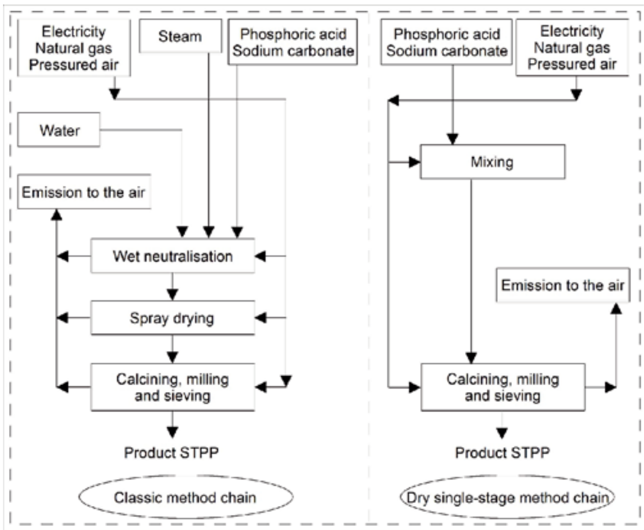


**Figure 1.** System boundaries and streams of material flows for classic spray two-stage method CM and dry single-stage method DSM

**Compared methods of sodium tripolyphosphate production**

Variant I – classic method

In the classic spray dry, two-stage condensation method of STPP production (Fig. 2), at first, in neutralization units, diluted (to ~30% $P_2O_5$) phosphoric acid (thermal or purified wet-process phosphoric acid) is neutralized with sodium hydroxide or carbonate corresponding to that obtained by a solution of orthophosphates with the molar ratio of $Na_2O/P_2O_5$ = 5/3. Next, STPP is obtained by a process of two-stage condensation of a solution of sodium orthophosphates. In the first stage of condensation, performed in the spray-drying unit, a liquid mixture of sodium orthophosphates is subjected to condensation

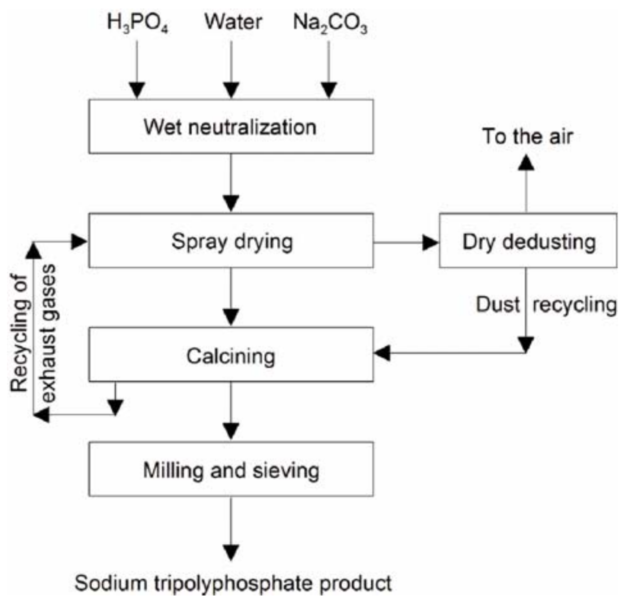


**Figure 2.** Flow sheet of the STPP production with the classic spray two-stage method CM

to obtain a mixture of tetrasodium diphosphate and disodium dihydrogen diphosphate. In the second stage of condensation, performed in rotary kilns, the mixture of tetrasodium diphosphate and disodium dihydrogen diphosphate is condensed by calcining to obtain the final product STPP, $Na_5P_3O_{10}$[26, 27]. The product undergoes milling, sieving, and packing.

Combustion gases from the rotary kiln pass through a dedusting bag filter and is then recycled into the process. The classic spray method requires energy for drying and calcining of phosphates. Higher energy consumption arises from the necessity of using diluted phosphoric acid in the neutralization process[28].

Variant II – dry single-stage method

In the dry single-stage condensation method (Fig. 3), a mixture of sodium carbonate and some part of the recycled final STPP product is neutralized with concentrated phosphoric acid (~53% $P_2O_5$). Single-stage condensation is performed by calcining in rotary kilns to obtain the final product STPP, $Na_5P_3O_{10}$. STPP recycling improves flow rate of the product and protects against agglomeration of the powder and also facilitates the transport of the mixture into the rotary kiln, where the orthophosphates are condensed into pyrophosphates, and converted into the final product STPP. This dry single-stage method in which an expensive spray drying operation has been eliminated is less expensive than the classic spray method[14].

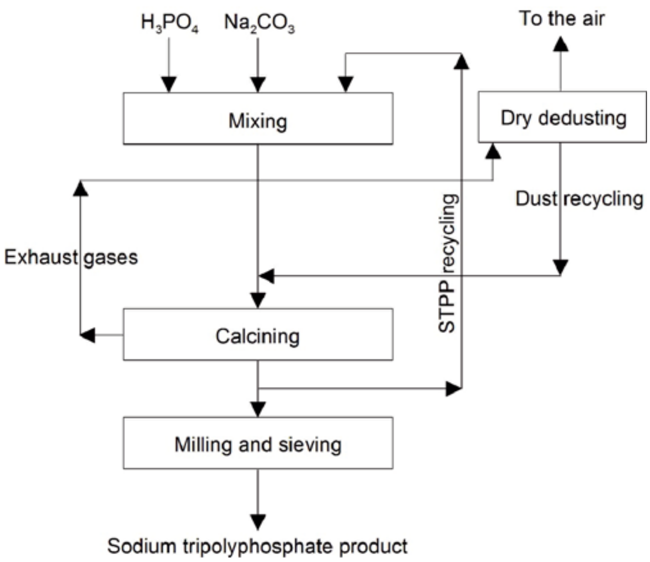


**Figure 3.** Flow sheet of the STPP production with the dry single-stage method DSM

The process parameters for the respective stages of the dry single-stage condensation method are as follows:

a: mixing – in this stage, sodium carbonate is mixed with phosphoric acid containing ~75% $H_3PO_4$ and recycled STPP (weight ratio STPP/batch = 2.5/1 or 5/1)

b: calcining – calcining time is 45–60 minutes at 350–550°C[29].

The obtained salt mixture is calcined in the same way as in the classic method. The calcining product is STPP in the form of low-temperature Phase II when the calcining temperature does not exceed 400–430°C or in the form of high-temperature Phase I when calcining is performed at >500°C[6, 30, 31].

In analyses of the possibility of implementing the one-step method, it is assumed that in a classic STPP production unit, the neutralization and spray drying stages would be replaced with a mixing stage. Other devices would remain unchanged.

The crucial advantage of the dry single-stage method is its ability to save on the consumption of energy compared to the classic spray two-stage method. Energy savings were estimated to be 4.92 GJ/t of STPP produced by DSM, compared to STPP produced by CM[13, 31]. Single-stage production eliminates the spray drying and neutralization stages. It can be estimated that the reduction in electricity consumption will be 72.5 kWh/t STPP[6].

The new method creates the opportunity for significant progress in reducing the environmental impact of STPP production. Its advantage is that this progress has been achieved mainly through the use of new technological and design solutions, the basic elements of the activities proposed in the cleaner production method[28, 32].

STPP obtained by both methods, contains over 94% of the main component, meeting the standard requirements.

Economic assessment of STPP production - evaluation of the STPP production costs

The production costs of STPP obtained by CM and single-stage DSM were compared with the following assumptions: amortization of 8% and repairs at 50% of amortization costs. Capacity was 40,000 t/y for both methods. Investment costs were estimated to be 18.67 million EUR for CM and 9.335 million EUR for DSM.

## RESULTS AND DISCUSSION

### Overall LCA analysis results

In Table 1 is presented Life Cycle Inventory (LCI) analysis containing consumption figures of raw materials and energy and emissions of fumes and dusts for both compared STPP production methods. The data on the consumption figures of raw materials and energy used for the manufacturing of STPP with the classic method is based on our previous publication[14]. The data for the dry single-stage condensation method were based on our research[6, 14, 33].

There is no release of wastewater and solid waste from these STPP production processes. The results of the LCA analysis after the characterization stage, including 16 impact categories, were presented for both variants (classical and single-stage methods) in Table 2 and Figure 4.

For each analyzed environmental aspect, the potential impact of STPP production using the single-stage method was lower than for the classical method. The reduction of potential impact is the most important for the depletion of the ozone layer (by 28%), climate change (by 23%), and depletion of resources (by 20%). This is a result of the reduction of the energy demand of the process (gas, steam) in the single-stage method of STPP production. In most of the other categories, this impact decreased by 1–5%.

After the characterization stage, each impact category is expressed in different units, so on the basis of these results, it is not possible to determine their share in creating the whole impact of the STPP process on the environment.

**Table 1.** Life Cycle Inventory (LCI) of STPP production methods: balance sheet data for CM and DSM technologies per functional unit

| Inputs | Amounts per functional unit | |
|---|---|---|
| | Classic method (CM) | Dry single-stage method (DSM) |
| Phosphoric acid 75% [kg] | 1065 | 1053 |
| Sodium carbonate (98% $Na_2CO_3$) [kg] | 735 | 729 |
| Water [kg] | 1250 | 0 |
| Energy – natural gas [GJ] | 6.55 | 1.63 |
| Energy – steam [GJ] | 1.0 | 0 |
| Pressured air [$m^3$] | 38 | 1 |
| Electric energy [GJ] | 0.288 | 0.261 |
| *Outputs – emitted fumes and dusts* | | |
| Sodium carbonate dusts [kg] | 0.3 | 0.3 |
| Phosphoric acid fumes [kg] | 0.22 | 0.22 |
| Sodium phosphates dusts [kg] | 1.8 | 1.8 |
| STPP dusts [kg] | 0.28 | 0.20 |
| $SO_2$ [kg] | 0.11 | 0.055 |
| $NO_x$ [kg] | 0.15 | 0.09 |
| $CO_2$ [kg] | 1013.8 | 700.0 |

**Table 2.** Midpoint results of the life cycle impact assessment (LCIA) characterization

| No. | Impact categories | Variant I Classic method (CM) | Variant II Dry single-stage method (DSM) |
|---|---|---|---|
| 1 | Climate change | 2900.0 | 2220.0 |
| 2 | Ozone layer depletion | 0.000178 | 0.000128 |
| 3 | Human toxicity, cancer effects | 0.0000979 | 0.0000937 |
| 4 | Human toxicity, non-cancer effects | 0.000127 | 0.000123 |
| 5 | Particulate matter | 3.11 | 3.06 |
| 6 | Ionizing radiation, effects on human health | 373 | 362 |
| 7 | Ionizing radiation, effects on ecosystems (temporary) | 0.00103 | 0.000998 |
| 8 | Photochemical ozone formation | 8.07 | 7.61 |
| 9 | Acidification | 51.6 | 50.6 |
| 10 | Terrestrial eutrophication | 26.4 | 25.1 |
| 11 | Freshwater eutrophication | 0.811 | 0.784 |
| 12 | Marine eutrophication | 2.03 | 1.91 |
| 13 | Freshwater ecotoxicity | 1720.0 | 1660.0 |
| 14 | Land use | 15300.0 | 14800.0 |
| 15 | Water resource depletion | 31.0 | 29.1 |
| 16 | Abiotic depletion | 0.000000938 | 0.000000757 |

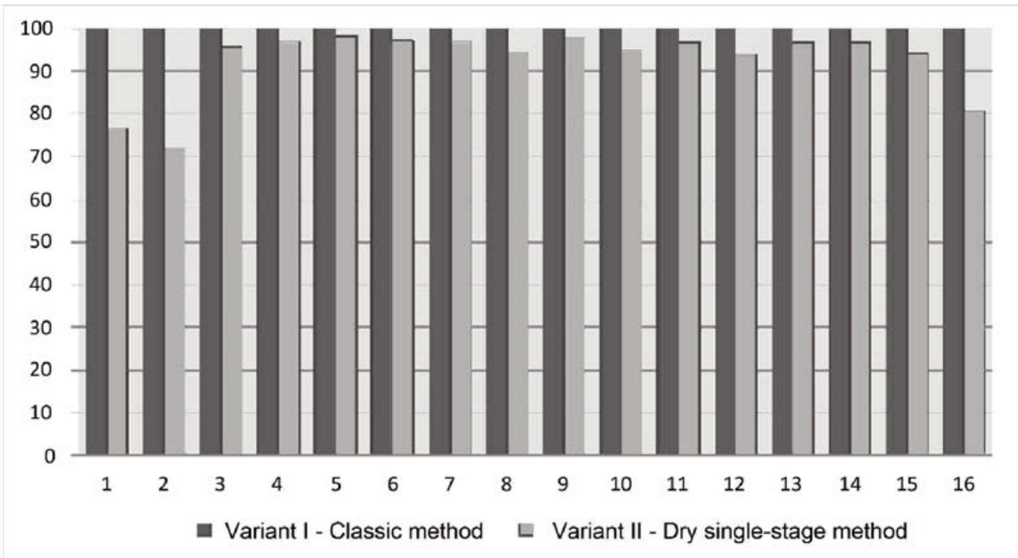


**Figure 4.** Histogram of characterization for life cycle of STPP production, estimated for both compared variants (classic and dry single-stage methods). Numbering of the impact categories as in Table 2. The largest impact is graduated to 100%, and the smaller ones are related to it

To present the results in an aggregated way, weighing is used, allowing for the presentation of the results of LCIA as a single indicator. According to the recommendation of[25] all impact categories have the same weighting factor of 1.

Weighing results were presented in Table 3. The cumulative results of the impact indicator for both methods of STPP production were 465.7 for the classic method and 444.4 for the single-stage method. Pt points are defined as the ratio of the total annual environmental load (caused by emissions, land use, depletion of resources) in Europe to the number of inhabitants. The total potential environmental load for the single-stage method (option II) is about 4.6% lower than for the classical method (option I).

**Table 3.** Midpoint results of the life cycle impact assessment (LCIA) weighting

| No. | Impact categories | Classic method (CM) | | Dry single-stage method (DSM) | |
|---|---|---|---|---|---|
| | | results | [%] | results | [%] |
| 1 | Climate change | 21.3 | 4.6 | 16.3 | 3.7 |
| 2 | Ozone layer depletion | 0.549 | 0.1 | 0.39 | 0.1 |
| 3 | Human toxicity, cancer effects | 177.0 | 38.1 | 170.0 | 38.2 |
| 4 | Human toxicity, non-cancer effects | 16.0 | 3.4 | 15.4 | 3.5 |
| 5 | Particulate matter | 43.0 | 9.2 | 42.2 | 9.5 |
| 6 | Ionizing radiation, effects on human health | 22.0 | 4.7 | 21.3 | 4.8 |
| 7 | Ionizing radiation, effects on ecosystems (temporary) | 0 | 0 | 0 | 0 |
| 8 | Photochemical ozone formation | 16.9 | 3.6 | 15.9 | 3.6 |
| 9 | Acidification | 72.9 | 15.6 | 71.5 | 16.1 |
| 10 | Terrestrial eutrophication | 10.1 | 2.2 | 9.61 | 2.2 |
| 11 | Freshwater eutrophication | 36.5 | 7.8 | 35.4 | 8.0 |
| 12 | Marine eutrophication | 8.07 | 1.7 | 7.57 | 1.7 |
| 13 | Freshwater ecotoxicity | 13.2 | 2.8 | 12.7 | 2.9 |
| 14 | Land use | 1.62 | 0.3 | 1.56 | 0.4 |
| 15 | Water resource depletion | 26.2 | 5.6 | 24.7 | 5.6 |
| 16 | Abiotic depletion | 0.000625 | 0.0 | 0.000505 | 0.0 |
| Sum | | 465.7 | 100.0 | 444.4 | 100.0 |

The highest impact in weighing results was observed for the category: human toxicity – carcinogenic (38%), acidification (16%), emission of particulate matter (9%), eutrophication of fresh water (8%), and depletion of fresh water resources (about 6%). Each of the other categories represented less than 5% of the total impact.

After the weighting step, it was shown that the total potential environmental impact for the single-stage method (variant II) was lower by only 4.6% compared to the classical method (variant I). For the single-stage method, the potential carcinogenic effect on human health decreased by 4.3% compared to the classical method, for acidification by 1.9%, for particulate matter emission by 1.7%, for fresh water eutrophication by 3.2%, and for the depletion of fresh water resources by 5.9%. This mainly resulted from a decrease in $H_3PO_4$ consumption by 1.1%. The use of phosphoric acid has a decisive influence (over 70% in both cases) on the potential environmental impact for the STPP technology being studied. Another factor affecting the quality of the environment and human health in the whole life cycle for both processes is sodium carbonate consumption (18%). Energy carriers (primary and secondary) account for 8.1% of the total impact of CM and 5.9% of the total impact of DMS.

The environmental impacts shown in Table 4 refer to all inputs and outputs connected within the scope of complete product systems (several hundred unit processes), thus taking into account not only activities related to the production of STPP, but also all suppliers. The reduction in direct fumes and dust emissions and water consumption will result in a potentially smaller environmental impact of about 0.9%.

**Table 4.** Calculation of STPP production costs

| Technology | | Classic method (CM) | | | Dry single-stage method (DSM) | |
|---|---|---|---|---|---|---|
| Capacity [t/y] | | 40,000 | | | 40,000 | |
| Investment cost [EUR] | | 18,670,000 | | | 9,335,000 | |
| Amortization [%] | | 8 | | | 8 | |
| No | Calculation position | Consumption figure [t/t)] | Price [EUR] | Cost [EUR/t] | Consumption figure [t/t] | Cost [EUR/t] |
| 1 | Raw materials | | | 679 | | 672 |
| | Phosphoric acid 75% [t/t] | 1.065 | 478.41 | 509 | 1.053 | 504 |
| | Sodium carbonate 98% [t/t] | 0.735 | 228.71 | 168 | 0.29 | 167 |
| | Water [$m^3$/t] | 1.25 | 1.40 | 2 | 1.25 | 2 |
| 2 | Purchase costs | | | 30 | | 30 |
| | Phosphoric acid 75% [kg/t] | 1.065 | 23.34 | 25 | 1.053 | 25 |
| | Sodium carbonate 98% [kg/t] | 0.735 | 7.00 | 5 | 0.729 | 5 |
| 3 | Total material costs (1+2) | | | 709 | | 702 |
| 4 | Technological energy | | | 113 | | 54 |
| | Natural gas [GJ/t] | 6.55 | 9.33 | 61 | 1.63 | 15 |
| | Steam [GJ/t] | 1 | 9.33 | 9 | 0 | 0 |
| | Electric energy [kWh/t] | 80 | 0.48 | 42 | 7.5 | 3.6 |
| 5 | Total direct costs (3+4) | | | 823 | | 756 |
| 6 | Chemical analyses | | | 4 | | 4 |
| 7 | Environmental fees | | | 2 | | 1 |
| 8 | Maintenance and repairs | | | 19 | | 9 |
| 9 | Amortization | | | 37 | | 19 |
| 10 | Service of production process | | | 4 | | 4 |
| 11 | Technical supervision salaries | | | 3 | | 3 |
| 12 | Production unit cost (5-11) | | | 891 | | 795 |
| 13 | Administrative costs [%] | | 3.0 | 27 | | 24 |
| 14 | Factory production costs (12+13) | | | 918 | | 819 |
| 15 | Cost of sales | | | 47 | | 47 |
| 16 | Total production cost (14+15) | | | 965 | | 866 |
| | [%] | | | 100 | | 89.7 |

**Economic results: calculation of STPP production costs**

Calculation of STPP production costs was presented in Table 4. Consumption figures for raw materials and utilities were taken from Table 1. The findings presented above show that the cost of STPP production by DSM maybe 10.3% lower than that of CM. However, the most important factor is the cost of raw materials, which is upwards of 75% of the total manufacturing costs. Moreover, the dry, single-stage method does not require any additional employment during operation. The investment costs are also relatively low. The cost of investment for the dry, single-stage method is half that of the classic method.

**Technological quality evaluation**

The assessment of the technological quality of these two methods of STPP production is summarized in Table 5. LCA indicators were taken from Table 3, the value of production costs from Table 4. The degree of validity $a_j$ was presumed to be 4 in the case of environmental effects and 2 for production costs.

The results of the assessment show that CM has a lower technological quality (by 6.5%) in comparison with DSM. Partial environmental quality was lower by 4.4% but partial economic quality was lower by 10.3%, mainly due to the lower (on average 52%) energy costs for DSM.

## CONCLUSIONS

The technological quality method was used to compare two methods of STPP production. The first method studied was the classic spray method (CM) and the second was a dry, single-stage method (DSM). The assessment criteria were environmental, based on an LCA evaluation and economic, based on production costs evaluations. The technological quality assessment showed that CM had 6.5% lower technological quality in comparison with DSM. LCA environmental analyses showed that the partial environmental quality of DSM was lower by only 4.4% compared to CM. The economic partial quality of the STPP production costs of DSM was 10.3% lower compared to CM mainly due to lower energy costs. However, the most important factor is the cost of raw materials, which is upwards of 75% of the total STPP manufacturing costs.

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**Table 5.** Comparative evaluation of the technological quality of two STPP production methods

| Technological quality assessment method | Scoring of STPP production methods [points] [F] | | Technological quality assessment value | | | | Technological quality $Q_T$ [points] | |
|---|---|---|---|---|---|---|---|---|
| | CM | DSM | criterion $w_c$ [1 point =] | [points)] $F/w_c$ CM | [points)] $F/w_c$ DSM | Degree of validity $a_j$ | CM | DSM |
| Environmental | | | | | | | $Q_{EN}$ | |
| LCA impact indicator | 465.7 | 444.4 | 4.66 | 100.0 | 95.6 | 4.0 | 400.0 | 381.4 |
| Economic | | | | | | | $Q_{EC}$ | |
| Production cost [EUR/t] | 965 | 866 | 9.65 | 100.0 | 89.7 | 2.0 | 200.0 | 179.4 |
| $Q_T$ | | | | | | | 600.0 | 560.8 |
| [%] | | | | | | | 100 | 93.5 |

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