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Life Cycle Analyses of Fertilizers: Carbon Emissions as a Measure of Energy Efficiency

Vladimir N. Bashkin*,
Andrey O. Alekseev,
Institute of Physico-Chemical and Biological Problems of Soil Science of the Russian Academy of Sciences,
Institutskaya str., 2, Pushchino, Moscow region, 142290, Russia

Аннотация

Using the analysis of the life cycle of fertilizers, it is shown that the values of greenhouse gas emissions can be considered as an indicator of energy efficiency. Taking into account the huge array of data accumulated in recent years on greenhouse gas emissions (primarily CO_2 and methane), it is possible to consider the problem of energy efficiency (carbon dioxide emissions occur during fuel combustion, first of all, as well methane and CO_2 as precursors for N fertilizer) in the chain from fertilizer production to their logistics, application, production and waste disposal. Relevant examples are given in the text of the article. It is shown, that an increase in energy efficiency in the considered life cycle of fertilizers, from production to utilization of agricultural waste, can significantly reduce the role of agricultural production in undesirable GHG emissions. It should be emphasized that reducing the potential of GHG emissions in the production of fertilizers depends on the source of energy used and the transfer of power plants from coal to gas, and especially RES, will be the most significant. When growing products, factors related to the use of modern farming systems based on accurate fertilization, the use of electronic soil maps, precision farming and increasing the efficiency of fertilizer use, in particular, nitrogen and phosphorus, play a very important role.

Ключевые слова: LCA; fertilizer production; carbon emission; nitrogen emission; energy efficiency; logistics; fertilizer application; agricultural waste recycling.

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Анализ жизненного цикла удобрений: эмиссия углекислого газа как показатель энергоэффективности

Башкин В.Н.*,
Алексеев О.А.,
Институт физико-химических и биологических проблем почвоведения РАН,
142290, Россия,
Московская обл., г. Пущино,
ул. Институтская, д. 2

Abstract

С использованием подходов анализа жизненного цикла удобрений показано, что величины эмиссии парниковых газов можно рассматривать как показатель энергоэффективности. Принимая во внимание огромный массив данных, накопленных за последние годы по выбросам парниковых газов (в первую очередь CO_2 и метана), можно рассмотреть проблему энергоэффективности (выбросы углекислого газа происходят, прежде всего, при сжигании топлива, а также метана и CO_2 как предшественников азотных удобрений) в цепочке от производства удобрений до их логистики, применения, производства и утилизации отходов. Соответствующие примеры приведены в тексте статьи. Показано, что повышение энергоэффективности в рассматриваемом жизненном цикле удобрений от производства до утилизации сельскохозяйственных отходов может значительно снизить роль сельскохозяйственного производства в нежелательных выбросах парниковых газов. Следует подчеркнуть, что потенциальное сокращение выбросов парниковых газов при производстве удобрений зависит от используемого источника энергии, и перевод электростанций с угля на газ будет наиболее значительным. При выращивании продукции очень важную роль играют факторы, связанные с использованием современных систем земледелия, основанных на точном внесении удобрений, использовании электронных почвенных карт, точном земледелии и повышении эффективности использования удобрений, в частности азота и фосфора.

Keywords: оценка жизненного цикла; производство удобрений; выбросы углерода; выбросы азота; энергоэффективность; логистика; внесение удобрений; переработка сельскохозяйственных отходов.

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Авторы заявляют об отсутствии конфликта интересов.

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Introduction

In the mineral fertilizers industry, the main pollutants released into the atmosphere include NO_x, CH_4, SO_2, SO_3, H_2SO_4, CO, fluorine compounds, NH_4NO_3. The production of ammonia, mineral fertilizers and inorganic acids requires large amounts of energy, usually obtained by burning organic fuels with the release of significant amounts of greenhouse gases. At the same time, some enterprises (for example, for the production of carbamide) partially use the resulting CO_2 as a feedstock, which reduces the emission of carbon dioxide. Nevertheless, the work of most enterprises is accompanied by emissions into the atmosphere associated with the combustion of natural gas, coal or diesel fuel in turbines, boilers, compressors and other systems for generating energy and heat. These emissions cannot be considered indicators that correctly determine the level of technology development, since they often depend on the raw materials used and the type of fuel and determine to a greater extent the technique and technology of energy production.

At the same time, one of the most important factors is energy efficiency. Thus, in Russia, the long stage of restoration and modernization of production facilities put into operation in the 1970s and 1980s in the Russian mineral fertilizers industry was completed by the end of 2010. Further expansion of existing capacities and deeper modernization are associated with a sharp increase in capital expenditures. As for energy efficiency, the basic principles of regulation in the field of energy conservation and energy efficiency improvement are laid down in the Federal Law of November 23, 2009. Federal Law No. 261 “On Energy Saving and Energy Efficiency Improvement and on Amendments to Certain Legislative Acts of the Russian Federation” and the relevant standard GOST R ISO 50001-2012.

The consumption of energy resources is inextricably linked with the problem of the impact on the environment, which is exerted by energy generation and transport, as well as greenhouse gas (GHG) emissions as a result of the combustion of hydrocarbon fuels. In the production of nitrogen fertilizers, a significant part of energy is consumed, in particular for the binding of atmospheric nitrogen necessary for the production of ammonia. During the production of ammonium nitrate, nitric acid from ammonia, sulfuric acid from sulfur, useful energy resources are produced that can be used to generate electricity using steam turbines. The release of phosphorus-containing fertilizers requires energy for the production of phosphoric acid, its further processing into finished products. Despite the fact that large amounts of energy are always consumed in the fertilizer industry in processes that take place at high temperatures and pressures, these industries have become more energy-efficient due to the improvement of the technologies used. Ammonia plants built in 1990th consumed approximately 30% less energy per ton of nitrogen compared to those that were put into operation in 1970th.

Among the enterprises of the industry under consideration, those enterprises that produce sulfuric acid (from sulfur) and nitric acid are suppliers of energy resources, such as high, medium or low pressure steam, or hot water. If all thermal energy is converted into electricity by means of a steam turbine, then supplies to the side of useful energy resources will be significantly reduced, but at the same time the generated electricity will be used directly in production. This is already being considered as one of the ways of energy efficiency.

It should be noted that during the production of mineral fertilizers, CO_2 emissions may increase, but the overall effect is compensated by high yields. Agriculture is one of the areas of production that significantly affects the emission of greenhouse gases, as well as consuming a large amount of energy. At the same time, energy consumption and greenhouse gas emissions are often directly proportional. Therefore, the most important way to reduce GHG emissions is to increase the energy efficiency of agriculture.

According to [2] the implementation of energy-saving policy in Russia, improvement and implementation of new energy-efficient technologies, energy-efficient equipment and machinery, rational use of energy resources will reduce specific energy consumption in the production of agricultural products, i.e. reduce the energy intensity of production and reach the planned level of its reduction — to 2030 by 60% and to 2035 by 65%.

There are four directions of energy saving in agriculture:

• absolute reduction of the amount of consumed energy due to rationalization of management methods, increased intensification, introduction of energy- and resource-saving production technologies;

• replacement of expensive and scarce energy resources with less scarce ones;

- expanding the use of non-traditional and renewable energy sources;
- changing the management system of the organization, building and putting into practice the organizational and economic mechanism of energy saving.

Taking into account the huge amount of data accumulated in recent years on greenhouse gas emissions (primarily CO_2 and methane), it is possible to consider the problem of energy efficiency (carbon dioxide emissions occur primarily during fuel combustion, as well as the use of methane and CO_2 as precursors of nitrogen fertilizers) in the chain from fertilizer production to their logistics, application, production and disposal of waste.

Since the vast majority of GHG emissions are caused by energy consumption processes, therefore, the growth of energy efficiency plays a decisive role in the impact on the level of emissions. Over the period 1990—2017, the energy intensity of Russia's GDP decreased by 30%, the energy intensity of world GDP — by 35%. This was a key factor in curbing CO_2 emissions, while the contribution of the process of reducing the carbon intensity of energy consumed (depends on the fuel structure) remains significantly less significant. In the future, the leading role of the energy efficiency factor will remain [3].

Therefore, the purpose of this article is to analyze the associated processes of energy consumption and greenhouse gas emissions in the system "production of mineral fertilizers — transportation — application in agroecosystems — utilization of agricultural waste" and to assess energy efficiency factors. At the same time, the size of GHG emissions at all stages of the life cycle can be considered as a measure of energy efficiency.

1. Fertilizer production

The production of mineral fertilizers, as part of the chemical industry (and at the same time heavy industry) is one of the most energy-intensive industries and can play a crucial role in the implementation of energy conservation and emission reduction commitments. It is shown that among the factors that can lead to a reduction in CO_2 emissions in China's heavy industry, the structure of industry (IS), investments in fixed assets (F) and historically established emissions of pollutants should be taken into account. At the same time, energy efficiency (EE) is a key factor in reducing carbon dioxide emissions. The implementation of a mandatory emission reduction policy can reduce CO_2 emissions [4].

The chemical industry in Russia accounts for about 2% of the country's primary energy consumption and 2.5% of total greenhouse gas emissions, of which 60% are emissions from production processes and fuel combustion. The remaining 40% relate to indirect emissions related to electricity and heat consumption. It is expected that the industry will continue to grow rapidly over the next two decades, and in order to limit the growth of energy consumption, it will need to implement cost-effective energy conservation measures. When implementing all identified measures in 2030 greenhouse gas emissions may be lower than today's levels. However, in the absence of these changes, emissions will increase by approximately 85%.

Energy efficiency improvement involves the installation of more energy-efficient equipment at chemical plants, the optimal use of catalysts and the use of more efficient ethylene cracking technologies that reduce energy consumption. The highest profitability and the most significant potential is distinguished by a set of measures to improve the energy efficiency of equipment of chemical enterprises (conveyor engines, mixing machines, etc.). With their help, it is possible to achieve energy savings in the amount of 6.3 million tons of CU and reduce emissions by 6.5 million tons of CO_2-e per year in 2030. It is also necessary to implement a number of measures to improve production processes and catalysts that will help reduce the intensity of emissions in chemical processes. The most important is the capture and/or destruction of nitrous oxide (N_2O) in waste gases during the production of nitric acid. With the help of certain filtration technologies (catalytic decomposition or catalytic reduction), it is possible to accelerate the decomposition of N_2O in waste gases. The implementation of this measure will reduce emissions, but is highly costly. Further, it is necessary to change the structure of the fuel balance of the chemical industry in order to switch to fuel that emits fewer greenhouse gases during combustion, for example, the transition of chemical enterprises from oil and coal to gas. The introduction of carbon dioxide capture and storage technology can also be considered. This is an emerging technology that is expected to capture carbon dioxide released during fuel combustion and during production processes at chemical plants (for example, in the production of ammonia).

Thus, the largest Russian producer of mineral fertilizers — PJSC PhosAgro, which, according to the

Russian Association of Fertilizer Producers, occupies 24% of the market, plans to reduce greenhouse gas emissions by 14% by 2028 compared to 2018. For this, for example, it has an energy efficiency program for energy conservation, reduction of consumption and losses [1]. Increasing the use of "green" electricity is part of PhosAgro's climate strategy, under which greenhouse gases alone are planned to reduce emissions by 14% from the base level of 2018 by 2028 for all three coverage areas.

The Energy Efficiency Strategy defines the following objectives (Table 1):

- reduction of greenhouse gas emissions with an increase in production;
- improving the energy and environmental efficiency of the main technological processes;
- reduction of energy and carbon intensity of manufactured products;
- entering new emerging markets for green products.

As a result, the specific energy consumption per unit of manufactured products and semi-finished products decreased from 5.58 GJ/t in 2018 and amounted to 5.06 GJ/t in 2021. At the same time, there was a decrease in the consumption of all types of natural fuels, even the consumption of the most environmentally friendly natural fuel — methane, decreased during this period to 0.075 m^3/t of products.

PJSC PhosAgro consistently works to reduce the carbon footprint of its products. This includes requirements for suppliers of goods and services (Table 1).

Let's look at a few more examples of Russian enterprises producing mineral fertilizers.

So, PJSC "Mineral Fertilizers" Perm, Russia, is one of the largest producers of nitrogen fertilizers in the Urals and Western Siberia. It produces anhydrous liquefied ammonia, technical aqueous ammonia, carbamide, as well as low-temperature liquid carbon dioxide and high-pressure liquid carbon dioxide.

For this enterprise, it was proposed to build a photovoltaic solar power plant on its territory, which is designed to generate electric current with its subsequent use within the internal power grid of the enterprise. This power plant can be installed both on the roof of a building and on the surface of vacant land plots. It is possible to install rechargeable batteries that will ensure stable operation of the redundant load in case of external power failure [5].

The enterprises-producers of nitrogen fertilizers in the Perm Region are considered. On the example of one of the largest producers of nitrogen fertilizers in the region, data on the material flows of ammonia production was collected [6]. The calculation of the carbon footprint of ammonia production at the enterprise in question was carried out in accordance with the methodological guidelines approved in Russia (Order of the

Table 1. List and main characteristics of the existing metrics that were introduced to monitor performance indicators within the framework of the climate strategy of PJSC "PhosAgro"

Таблица 1. Список и основные характеристики существующих метрик, которые были введены для мониторинга показателей эффективности в рамках климатической стратегии ПАО «ФосАгро»

Name of metrics, unit of measurement	Years			
	2018	2019	2020	2021
The volume of total global emissions (coverage 1 + 2) per unit of currency of total revenue, t CO_2-eq. / million US dollars	1552.3	1467.1	1621.6	975.5
The volume of total global emissions (coverage 1 + 2) per equivalent of one full-time employee, t CO_2-eq.	331.0	321.6	319.6	304.0
Purchased electricity per unit of manufactured products and semi-finished products, thousand kWh /t	0.071	0.069	0.068	0.066
Energy efficiency improvement costs, million rubles	-	82.0	10500.0	17.4
Share of raw material suppliers who provided the necessary baseline data on greenhouse gas emissions (coverage 3), %	-	-	4.0	2.7

Ministry of Natural Resources of the Russian Federation No. 300 dated June 30, 2015). According to this document, greenhouse gas such as carbon dioxide (CO_2) is subject to mandatory accounting for ammonia production. It is established that the annual production generates 2.433 million tons of CO_2. According to the calculated data, there are 2,027 tons of CO_2 per 1 ton of ammonia, which meets the requirements of the criteria for sustainable (including "green") development projects in the Russian Federation — the total emission is below 2,104 tons of CO_2 per 1 ton of ammonia. But in order to clarify the amount of total emissions, a more detailed consideration of electricity sources is required, as well as an analysis of indirect CO_2 emissions per 1 ton of ammonia (coverage 2).

It is important to note that according to the results of the data analysis, it was revealed that there is no flow of CO_2 extracted at the enterprise for further use as raw materials for the production of marketable products. It was also found that as a result of recent measures, it was possible to reduce the consumption of natural gas to 1,275 m^3 per ton of ammonia (Table 2). In the future, it is planned to further reduce the consumption of natural gas to the level of 1100 m^3 per ton of ammonia, which will reduce the annual volume of CO_2 by 333.9 thousand tons.

Based on the results of the assessment of CO_2 emissions, as well as according to the analysis of technology and data on the main material flows of ammonia production, the main directions of the development of "green" projects that reduce the carbon footprint of ammonia production at the considered enterprise have been identified:

- processing of the extracted CO_2 fraction (for example, involving carbamide in the production process to create a protective environment for welding metals, for drying molds, for fire extinguishing);
- development and implementation of technologies to reduce the consumption of raw materials in the production of ammonia (for example, the installation of separation of combustible gases from the CO_2 fraction in the CO_2 purification department, reconstruction of the syngas compressor and steam turbine);
- increased energy efficiency as a consequence of the factors mentioned above.

Summarizing the materials given in this section, it can be concluded that currently the production of mineral fertilizers due to technological processes, even with the use of BAT, is associated with GHG emissions. However, increasing the energy efficiency of production entails an inevitable reduction in GHG emissions.

2. Fertilizer logistics

Transport logistics is the optimization of cargo transportation management, that is, the execution of operations for the movement and storage of raw materials, semi—finished products, work-in-progress objects, finished products from places of origin to places of consumption.

For example, when moving commodity batches of mineral fertilizers from producers and commercial intermediaries to consumers, a combination of road, rail and water modes of transport (specialized wagons and vehicles) is used.

The main goal of transport logistics in the agro—industrial complex, as well as logistics in general, is to reduce the cost of physical goods movement. This goal is achieved by observing the following fundamental principles: the fullest possible use of the carrying capacity or cargo capacity of vehicles; organization of cargo delivery without warehouses (using cross-docking

Table 2. Material flows during the production of 1 ton of ammonia (JSC "Azot" Uralchem", Berezniki) [7]

Таблица 2. Материальные потоки при производстве 1 тонны аммиака (ОАО «Азот» Уралхим», Березники) [7]

Incoming flows			Outgoing flows		
Name	Unit of measurement	Per 1 t of ammonia	Name	Unit of measurement	Per 1 t of ammonia
Natural gas	m^3	1275	NO_x emission	kg	1.86
Nitrogen	m^3	38			
Electricity	kWh	159	CO_2 emission	kg	1.45
Make-up water	m^3	3,65			

technology); multiplicity of the transport unit of cargo to the units of order, dispatch and warehousing (for example, the use of a container); standardization of containers; economies of scale and distance of cargo transportation, since in this case the costs per 1 ton-kilometer are minimal; the concentration of cargo flows on separate channels of distribution of goods and the rejection of uneconomical channels; delivery of goods using just-in-time technology. The implementation of these principles in practice makes it possible to achieve maximum economic efficiency for a transport, manufacturing or trading enterprise. It also determines the energy efficiency of mineral fertilizers transportation and optimizes GHG emissions.

Road transport produces a significant amount of GHG emissions, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Calculations of emissions from vehicles are based on data on total fuel consumption. The specific heat of combustion and emission factors for each type of fuel must be calculated taking into account the specifics of the fuel used. Taking into account the length of movement of mineral fertilizers, both energy consumption and GHG emissions are estimated.

The methodology for calculating emissions from fuel combustion from motor transport is divided into two parts: assessment of carbon dioxide emissions and assessment of emissions of other gases. The estimate of CO_2 emissions is best calculated based on the amount and type of fuel burned and the carbon content in it. The amount of oxidized carbon practically does not vary depending on the fuel combustion technology used. The assessment of emissions of other gases with a greenhouse effect is more complicated, since it depends on the type of car, fuel, vehicle operation characteristics, and the type of exhaust gas control technology.

Assessment of carbon dioxide emissions from fuel combustion by road

Calculation of carbon dioxide emissions from fuel combustion in internal combustion engines is recommended to be carried out on the basis of accounting for fuel types and engine types. Carbon dioxide emissions by this method are estimated as follows. First, the consumption of each type of fuel is estimated by type of transport (passenger, cargo, buses, special vehicles). Then the total CO_2 emissions are estimated by multiplying the amount of fuel consumed by the emissions factor for each type of fuel and type of transport according to the formula:

$$E = M \times K_1 \times CNV \times K_2 \times 44/12,$$

where E — annual CO_2 emissions in weight units (tons/year); M — actual fuel consumption per year (tons/year); K_1 — carbon oxidation coefficient in fuel (shows the proportion of burnt carbon), table 3; CNV — calorific net value (J/ton), table 3; K_2 — carbon emission factor (tons/J), table 3; 44/12 — the coefficient for converting carbon emissions to carbon dioxide.

Based on these data, let's consider an example of assessing the impact of tractor design on GHG emissions. Table 4 shows comparative calculations when performing transport work as part of Doutz-Fahr Agrotron L720 and Belarus 2022 tractors with a PST-12 trailer, John Deer 6110B and Belarus 82.1 tractors with a 2PTS-6 trailer within a farm. The Doutz-Fahr Agrotron L720 and Belarus 2022 tractors of the same traction class are distinguished by a more advanced gearbox from a foreign analogue, capable of realizing high performance properties. The gearbox of the John Deer 6110B tractor is also more perfect, it has 4 ranges of 6 gears, which contributes to a more rational use of operational properties compared to the Belarus 82.1 tractor [8]. The

Table 3. Coefficients for converting burnt fuel into CO_2 emissions for motor vehicles

Таблица 3. Коэффициенты для преобразования сгоревшего топлива в выбросы CO_2 для автотранспортных средств

Types of fuel	Calorific net value is the lowest, *CNV* TJ/thousand tons	Carbon emission factor, K_2, tC/TJ	Fraction of oxidized carbon, K_1
Gasoline	44.21	19.13	0.995
Diesel fuel	43.02	19.98	0.995
CNG	47.17	17.91	0.99
Natural gas	34.78	15.04	0.995

Table 4. Indicators characterizing transport units and GHG emissions
Таблица 4. Показатели, характеризующие транспортные единицы и выбросы парниковых газов

Key indicators	Transport units			
	Belarus 82.1+2PTS-6	John Deer 6110B+2ПТС-6	Belarus 2022+ PST-12	Doutz-Fahr Agrotron L720+ПСТ-12
Load capacity, kN	60.02	60.02	86.05	86.05
Average speed of movement, km/h	22.7	25.1	26.2	27.7
Speed utilization factor	0.77	0.77	0.77	0.77
Traction resistance of a trailer with a load, kN	4.35	4.35	6.06	6.06
Productivity, t/h	4.86	5.38	8.3	8.95
Working hour productivity, t	34	37.6	58.1	62.6
Fuel consumption per transported ton, kg/t	2.62	2.08	2.7	1.73
CO_2 emissions per ton transported, kg/t	8.216	6.522	8.446	5.425

calculation data on the technical parameters of various tractors and fuel use are given in Table 4.

The presented calculations indicate that the GHG emission is significantly influenced by the machine system as a whole, as well as individual tractors, grain and forage harvesters and other energy means. At the same time, it is very important to properly complete the units both from the point of view of reducing fuel consumption, reducing CO_2, CH_4, NO_X emissions, and the negative impact on the soil — over-compaction, erosion, unjustified use of chemicals and others.

Let's also consider a comparison of transport parameters that determine energy consumption and GHG emissions with 2 different wheat growing systems [9]. It is known that an optimized life cycle assessment is carried out to compare the global warming potential (GWP) and the use of primary energy in the production and delivery of traditional and organic wheat in the United States. The differences in the impact of agricultural resources, grain cultivation and transport processes are evaluated.

Logistics assessment and detailed analysis of transport chains, taking into account distances, were carried out using the Internet interface for specifying routes along the highway. Table 5 shows primary energy consumption (J) and global warming potential (GWP, measured in g CO_2-eq., 100-year time period) with an

Table 5. Estimation of the values of energy use and global warming potential in two wheat growing systems
Таблица 5. Оценка значений энергопотребления и потенциала глобального потепления в двух системах выращивания пшеницы

Process	Conventional wheat (reference case)		Organic wheat (reference case)	
	Energy use (J)	Global warming potential (g CO_2-eq.)	Energy use (J)	Global warming potential (g CO_2-eq.)
Fertilizer production	820	46	21	1.7
Nitrogenous	770	42	0.0	0.0
Phosphatic	50	3.8	21	1.7
Pesticide production	22	1.6	0.0	0
Fertilizer & pesticide transport	29	2.1	31	2.2
Fuel use	22	1.5	25	1.8
Fuel production	7.0	0.5	5.4	0.4

End of table 5

Окончание таблицы 5

Process	Conventional wheat (reference case)		Organic wheat (reference case)	
	Energy use (J)	Global warming potential (g CO_2-eq.)	Energy use (J)	Global warming potential (g CO_2-eq.)
Wheat farming	490	36	650	48
Tillage	450	32	600	42
Fuel production	37	4.4	49	5.8
N_2O emission from soil	n.a.	96	n.a.	96
GHG from manure storage	n.a.	n.a.	n.a.	5.1
Farm machinery production	85	7.3	85	7.3
Subtotal	1400	190	790	160
Flour transport (2000 km)	1900	140	1900	140
Fuel use	1600	110	1600	110
Fuel production	310	25	310	25
Total	3300	330	2700	300

optimized wheat production and delivery system in the amount of 670 g required for 1 kg of loaf of bread. The traditional wheat growing system and the use of mineral fertilizers and the organic system are evaluated.

From the data in this table 5, it can be concluded that, although the organic wheat growing system requires slightly less energy use and is accompanied by lower GWP values, these differences are generally insignificant. It is shown that the GWP of a loaf of organic wheat bread weighing 1 kg is approximately 30 g CO_2-eq. less than that of a conventional loaf. However, it is necessary to take into account the transport shoulder. Thus, with longer transport routes for the delivery of wheat grain (more than 420 km), the differences between the two compared growing systems practically disappear. In addition, other factors are important, such as the accumulation of carbon in the soil and emissions of nitrous oxide from the two systems.

3. Fertilizer application to agroecosystems

In recent years, in Russia the energy intensity of agricultural production has been decreasing, but the share of energy consumption in the cost price has been steadily increasing. Thus, the cost of consumed energy resources in the cost of the main types of agricultural products averaged 26—35% (in 1985—1990 — 7—15%). High energy consumption indicators indicate a faster growth in the cost of energy carriers and low efficiency of using fuel and energy resources, which negatively affects the cost of production (Table 6).

Significant sources of emissions in agriculture in Russia are the direct release of nitrous oxide from agricultural soils (52557.0 thousand tons of CO_2-eq.) and CH_4 emissions from fermentation of domestic animals (39090.4 thousand tons of CO_2-eq.), while compared with 1990, their volumes decreased by 38,4 and 62,8%, respectively. In 2019, the contribution of nitrous oxide to total agricultural emissions was 59,6%, CH_4 — 39,5%, CO_2 — about 0,8% (Table 7) [11].

Organic agriculture is an environmentally safe and sustainable method of farming, the key features of which are the use of technologies for recycling organic carbon into nutrients: direct processing of manure, effective composting, disposal of residues. The use of organic fertilizers eliminates greenhouse gas emissions during the application of mineral fertilizers and during their production. Agrotechnologies such as mulching, reducing soil erosion and increasing soil fertility, increasing carbon turnover due to nutrient recycling have a positive effect on energy efficiency and GHG

Table 6. Energy intensity of agricultural production in Russia (according to [10])
Таблица 6. Энергоемкость сельскохозяйственного производства в России (по данным [10])

Types of products	Electricity, kWh/t	Fuel (heat), kg cf/t	Total energy consumption (energy intensity), kg cf/t	The share of energy consumption in the cost of production, %
Milk	340	190	230	34.5
Pork	2500	1900	2200	26.5
Beef	1700	800	1000	12.0
Eggs (1000 pcs.)	95	28	38	34.0
Cereals	130	120	140	31.5

Table 7. Sources of greenhouse gas emissions in agriculture in Russia in 1990—2019, million tons of CO_2-eq.
Таблица 7. Источники выбросов парниковых газов в сельском хозяйстве России в 1990—2019 гг., млн тонн CO_2-экв.

Source categories	GHG	1990	2000	2010	2017	2018	2019	Dynamics of reduction, 2019/1990, %
Internal fermentation of farm animals	CH_4	105.2	51.2	40.5	39.4	39.4	39.1	37.2
Manure and manure collection, storage and use systems	CH_4	13.4	5.6	4.5	5.3	5.4	5.4	40.3
	N_2O, direct emission	8.5	4.1	4.0	4.0	3.9	3.6	42.4
	N_2O, indirect emission	7.0	3.2	3.1	3.3	3.4	3.2	45,7
Rice cultivation	CH_4	0.9	0.5	0.6	0.6	0.6	0.6	66.7
Emissions from agricultural land	N_2O, direct emission	85.3	46.4	43.5	51.2	50.8	52.6	61.7
	N_2O, indirect emission	17.1	6.8	6.6	8.5	8.4	8.7	50.9
Liming of soils and application of urea	CO_2	10.2	1.0	0.8	0.8	1.0	0.9	8.8
Total		247.5	118.8	106.2	113.1	112.9	114.2	46.1

emissions. In animal husbandry, the use of energy-rich feeds in the diet, changing the duration, time and place of eating and drinking by animals can mitigate GHG emissions. However, with organic farming systems, as a rule, the production of marketable products decreases compared to traditional systems using mineral fertilizers.

In general, resource-saving agriculture is based on such principles as minimal mechanical tillage prior to seed planting, as well as when applying fertilizers, harvesting and other operations; preservation of plant residues on the soil surface (mulching), which allows protecting the soil from water and wind erosion, increasing its productivity, improving physical, chemical and biological properties of the soil; the use of differentiated crop rotations to control weeds, diseases and pests, improve land productivity under the influence of individual crops; effective management of pasture lands, etc. Integrated management of soil, water and biological resources contributes to the conservation, improvement and efficiency of their use.

The most energy-intensive technological process is tillage, which on average consumes 30—40% of the energy consumed [12]. The reduction of these costs, for example, the use of a ploughshare developed by the authors, kinematically connected to the rotary frame of the plough, allows reducing both energy costs and GHG emissions by 10% during plowing.

Studies on the effect of soil treatments on humus reserves conducted in the chernozem zone of Siberia, Russia, have shown that differentiated tillage is optimal, where the humus content in the 0—30 cm layer has changed from 8.12 to 8.56% over 39 years. The use of permanent dump tillage led to a decrease in the humus content in the 20—30 cm layer from 7.73 to 7.23%, but its increase was noted in the 0—20 cm layer from 8.38 to 8.52%. No-tillage and zero treatment led to an increase in humus in the 0—10 cm layer, but led to a decrease in the humus content in the soil layers by both 0—20 cm and 0—30 cm. Based on this, it can be concluded that the transition to No-Till technologies in this zone to enhance carbon sequestration in chernozem soil is an ineffective technique, although this contributes to energy efficiency due to lower plowing costs [13—18].

Reducing the consumption of fossil fuel and energy resources, the use of renewable energy sources in organic agriculture, primarily solar and wind energy, also contributes to reducing greenhouse gas emissions. The use of liquid biofuels (biodiesel from oilseeds) or mixed with conventional fuel definitely has advantages over conventional fuel in terms of emissions of pollutants into the atmosphere. In addition, carbon dioxide is absorbed during the cultivation of oilseeds themselves, but, on the other hand, their cultivation leads to direct and indirect greenhouse gas emissions. The factor of land use change is important. Therefore, oilseeds in temperate climates also need to be grown using organic technologies to meet their own energy needs.

Similar data were obtained when estimating N_2O and CO_2 emissions from tropical oil palm plantations. A significant influence of soil growing conditions was established, while the use of fertilizers did not always lead to an increase in GHG emissions [19].

Based on long-term studies, the balance of carbon dioxide in crop rotations with sugar beet was estimated [20]. The authors calculated that this indicator consists of:

- absorption of CO_2 by the main and by-products, plant residues, as well as fixation during humification of manure, fixation with soil carbonates, precipitation from the atmosphere (input articles);
- decomposition of plant residues and humus, soil respiration (increases when mineral fertilizers are applied), liming, decomposition of part of manure, removal by surface and groundwater, mineralization of humus (expenditure items).

The dry matter of sugar beet at a yield of 55.0—60.0 t/ha in the conditions of the chernozem region (Russia). It is able to bind about 24.8—28.5 t/ha of CO_2 with the main products (root crops).

The main agricultural methods of crop cultivation (plowing of tops and plant residues, liming, application of manure and mineral fertilizers) contribute to the emission into the atmosphere of about 8,7—11,7 t/ha of carbon dioxide per year, while binding in the organic matter of the soil (subject to the application of manure) of about 4,4—11,2 t/ha of CO_2 per year (according to various estimates).

Reducing the mineralization of humus reserves, organic fertilizers, plant residues through rational soil treatment, the introduction of scientifically based doses of fertilizers, optimization of soil acidity can reduce CO_2 emissions in the soils of beet crop rotations.

According to preliminary calculations, the carbon dioxide balance during the cultivation and processing of sugar beet in the considered region is either negative (since a large amount of CO_2 is bound by products), or close to equilibrium, i.e. beet farming is not a pollutant of the atmosphere with CO_2 emissions, and under certain conditions, it may meet the requirements of carbon farming.

A significant number of studies have been carried out to assess the impact of various energy-efficient agricultural technologies and improved "green" fertilizers on greenhouse gas emissions from soil in agroecosystems. Thus, the use of nitrogen fertilizers with the addition of humic acid leads to a controlled release of nitrogen, which is accompanied by an increase in the yield and digestibility of nitrogen, an increase in the efficiency of nitrogen use and a reduction in greenhouse gas emissions [21].

A detailed overview of the retrospective application of fertilizers in China is given [22]. A quantitative assessment of GHG emissions from the production and application of nitrogen fertilizers during the cultivation of wheat and corn in various provinces and agricultural regions of China was carried out. The authors showed that in the period 2015—2017, the average nitrogen doses for wheat and corn in the high-altitude fields of China were 222 and 197 kg ha^{-1}, respectively. At the same time, a total of 12.63 million tons per year were contributed to these crops. Nationwide, greenhouse gas emissions associated with the production of mineral nitrogen fertilizers were estimated at 41.44 and 59.71 million tons of CO_2 per year for the crops in question. At the same time, when applying these fertilizers, N_2O emissions due to denitrification processes, according to the authors, amounted to 35.82 and 69.44 Gg year^{-1}. The authors conclude that the production and application of mineral nitrogen fertilizers for wheat and corn on Chinese arable lands is an important source of greenhouse gas emissions in agriculture.

A field experiment was also conducted to study the effect of stabilized nitrogen fertilizer in combination with pig manure on rice yields and emissions of nitrous oxide (N_2O) and methane (CH_4) [23]. Four ways of applying various combinations of mineral and organic fertilizers were studied: urea (U); pig manure (PM); PM and urea (PM + U); PM and stabilized nitrogen fertilizer (urea plus 1% NBPT (N-(n-butyl) thiophosphoric triamide), 1% PPD (phenylphosphorodiamidate) and 2% DMPP (3,4-dimethylpyrazolphosphate)) (PM + U + I). As shown by the authors, in comparison with the PM variant, the PM + U variant significantly increased the total N_2O emissions, but when PM + U + I was introduced, no significant differences were found from PM in cumulative N_2O emissions. This indicates that the use of stabilized nitrogen fertilizer in combination with PM effectively reduces N_2O emissions. The total CH_4 emission when PM + U + I was introduced was lower than when PM and PM + U were introduced. Therefore, a stabilized nitrogen fertilizer in combination with PM can effectively reduce CH_4 emissions. The rice yield on the PM + U and PM + U + I variants did not differ significantly from the yield on the U and PM variants. Accordingly, the authors conclude that local traditional nitrogen application and PM return can provide sufficient nitrogen for rice growth. The total amount of GHG emissions at the production scale (yield-scaled emissions, YSE) in the PM variant was the highest, while in the PM + U + I variant there was a significant decrease in YSE values.

It was found that the emission of N_2O from agrozems never exceeded 5 mg of N_2O-N/ha per day if the soil contained less than 10 mg of available mineral nitrogen per 1 kg of soil. The introduction of N into the soil with fertilizers almost always led to an increase in the cumulative flow of N_2O from the soil. The largest cumulative flows of N_2O from soils were observed when cattle manure was applied, which was associated not only with the entry of a large amount of available N into the soil, but also with the entry of available C and moisture. The introduction of manure into the soil led to an increase in the spatial heterogeneity of N_2O emissions from soils, which significantly increased the measurement error.

The emission factor (EF), calculated as the proportion of nitrogen lost in the form of N_2O, in % of the total amount of nitrogen introduced with fertilizers, for sod-podzolic sandy loam soil in different years of the study was greatest for soils receiving high doses of N with mineral fertilizers (from 90 kg N per ha) and varied in different years from 0.5—1.8%. When applying green or organic fertilizers, the EF in the experiments did not exceed 0.62% [24].

Summarizing this section, it should be emphasized that the modern literature has accumulated a huge array of data on the assessment of GHG emissions from the cultivation of various crops in different regions of the world. Here are only some examples indicating the possibility of using these values as a measure of energy efficiency of agricultural production.

Within the framework of this article, it can be noted that the rational application of mineral fertilizers, as well as their various combinations with organic ones, leads to an increase in yields of cultivated crops and an increase in food safety. At the same time, the use of fertilizers leads almost everywhere to a largely inevitable increase in the emission of various greenhouse gases. For example, when nitrogen fertilizers are applied, the carbon- and nitrogen-mineralizing ability of soil organic matter (SOM) increases. This is accompanied by an increase in emissions of both carbon dioxide and nitrogen oxides. A similar effect is manifested in the denitrification of both the introduced nitrogen of mineral fertilizers and the mineralized nitrogen of SOM. In rice agroecosystems, the emissions of these GHGs are supplemented by methane emissions. In general, agroecosystems are a clean source of CO_2. Therefore, the question of the relationship between GHG emissions and energy efficiency in agroecosystems must necessarily be considered in the context of crop yield growth.

4. Waste utilization

A large amount of agricultural waste (AWs) is generated every day around the world due to the growing needs of a rapidly growing population, whose number exceeded 8 billion in 2022. It is necessary to develop a strategy for their timely use. It will also increase the sustainability of agriculture and food security. AWs is generated from various sources, including plant residues, agro-industrial complex, animal husbandry and aquaculture. The main component of plant residues and agro-industrial waste is cellulose (the most common biopolymer), lignin and hemicellulose (lignocellulose biomass). Waste and its recycling is a global problem. A recycling-based solution is needed. In this case, recycling can be aimed either at obtaining energy, or at returning to the biogeochemical cycle of the biophilic elements accumulated in waste. This will contribute both to the energy efficiency of agriculture as a whole and to the reduction of GHG emissions (see, for example, [25]

Using as an example the system of accumulation of agricultural waste in Jiangxi Province (China), it was investigated to what extent data on the assessment of resource flows and indicators characterizing the reduction of greenhouse gas emissions can be used to develop policy measures in the field of sustainable use of agricultural waste [26]. The authors showed that when the percentage of agricultural waste increases from 4.41% to 8.61%, the current potential for reducing greenhouse gas emissions subsequently increases by about 3.3 times. At the same time, the maximum potential for reducing GHG emissions may be 16.44×10^8 tons of CO_2-eq. in this province.

Agricultural waste is largely associated with biodegradable household waste. A large amount of nitrogen is stored in this garbage. It was noted that biodegradable household waste, for example, in China, mainly included food waste, waste paper and wood chips in the amount of 31.56, 29.55 and 6.45×10^6 $t{\cdot}a^{-1}$, respectively. Accordingly, the nitrogen reserves in China in these wastes were 65.31×10^4, 6.80×10^4 and 3.81×10^4 $t{\cdot}a^{-1}$. Nitrogen reserves in food waste provided 86% of the total nitrogen reserves in biodegradable household waste, which is equivalent to 11% of the actual absorption of mineral nitrogen fertilizers (6.20×10^6 t·a–1) by agricultural plants in China [27].

Another important problem is the recycling of animal waste. For this purpose, it is important to estimate the content of nitrogen (N) and phosphorus (P) in solid organic fertilizer obtained from cattle manure, for example, in the North-West of Russia [28]. The study compared the following approaches: normative indicators for Russia; data calculated by the mass balance method; average experimental data on the content of N and P in cattle manure; analysis of nitrogen and phosphorus content in organic fertilizer. The selected livestock complex with 1,250 heads and a manure yield of 70 tons per day^{-1} was considered. The authors established a difference between the calculated and experimental data, which was a maximum of 10%, but the experimental data and the established norms differed by more than 15%. Consequently, even an increase in the nutrient content of organic fertilizer by 10% makes it possible to increase the area of fertilized agricultural land from 451 to 526 hectares.

To calculate greenhouse gas emissions from livestock farms, initial data on livestock are needed. Calculations were carried out for a livestock farm, which has 6 thousand heads of cattle [29]. The calculated method determined the methane emission from the storage systems of cattle biomass on a livestock farm, which amounted to 27,600 kg / year of CH_4. In terms of CO_2 equivalent, methane emissions are 579.6 tons per year. The emission of N_2O during storage and use of biomass for the livestock farm in question is equal to 845.17 N_2O kg/year. In terms of CO_2 equivalent, this amounts to 262.0 tons per year. The sum of CH_4 and N_2O emissions in CO_2 equivalent from biomass collection and storage systems for the farm in question is 841.6 tons of CO_2 equivalent per year. According to the program developed by the authors for calculating the output of biogas from the waste of livestock farms, the daily production of biogas is calculated. For the livestock farm under consideration, the daily output of biogas was 9,850 m^3/day or 3.4 million m^3 per year.

The processing of organic waste in agriculture contributes to the circular economy by returning nutrients to the soil and reducing the need for mineral-based fertilizers [30]. Also, the use of manure makes it possible to create organic systems with a regulated and optimized GHG flow [31]. Table 8 shows the GHG coefficients for pasture ecosystems.

The main contribution to the formation of waste in Russia is created by the food and processing industry. When analyzing the data of the Ministry of Agriculture for 2015—2017, it was revealed that 15,635 thousand tons of agricultural crops account for about 335 thousand tons of primary and secondary waste obtained as a result of technological processes of converting raw materials into food products [43]. The authors carried out the data of calculations and selection of the optimal use of agricultural waste, with the highest energy efficiency and minimum values of the carbon footprint.

One of the alternative uses of waste is the burning of dry residue as fuel pallets. The physical properties of straw residues were considered. The density of the straw residue weighing 400 kg and a volume of 1 m^3 will be 0.4 kg /l. At the same time, the mass of the dry substance

Table 8. Greenhouse gases (GHG) coefficients (kg CO_2-eq. unit^{-1}) of farm facilities for horticultural crops production

Таблица 8. Коэффициенты выбросов парниковых газов (ПГ) (кг CO_2-экв. на единицу$^{-1}$) сельскохозяйственных объектов для производства садовых культур

Inputs	Unit	GHG Coefficient (kg CO_2-eq./unit	References
Human labor	h	0.36	[32]
Machinery	MJ	0.071	[33]
Electricity	kWh	0.608	[34]
Fuels			
Diesel	L	2.76	[33]
Fertilizers			
MWC / Industrial / on farm Composts	kg	0.040—0.063	[35–37]
Anaerobic digestate (AD)	kg	0.031	[38]
Nitrogen (N)	kg	5.29	[39]
Phosphate (P_2O_5)	kg	0.52	[39]
Potash (K_2O)	kg	0.38	[39]
Chemicals			
Insecticides	Kg	5.1	[40]
Fungicides	Kg	3.9	[41]
Herbicides	kg	6.3	[41]
Irrigation water	m^3	0.27	[32]
Plastic pipes PE	kg	2.2	[42]

will be 100 kg. The data of the heat of combustion (MJ/t) for the presented types of residues of vegetable raw materials were found. The conversion factor for CO_2 emissions from wood waste incineration is 0.068 tons of CO_2/ton of wood waste. Based on calculations, it is shown that the total amount of energy generated during the combustion of the total amount of waste can be 151.93 million. GJ per year (Table 9).

Table 9. The amount of energy generated by burning different types of vegetable raw materials (based on [43])

Таблица 9. Количество энергии, вырабатываемой при сжигании различных видов растительного сырья (на основе [43])

Type of vegetable raw materials	Mass of waste, million tons per year	Heat of combustion, MJ/t	The amount of energy generated during the combustion of the total amount of waste, mln GJ per year
Sunflower husk	7,1	17000	12.08
Rice husk	1,9	13300	25.92
Leftover corn	2,6	14650	38.18
Straw	41,4	15700	65.09
Cotton	7,7	14530	1.118
Legumes	65,1	14650	9.54
Total:		151,93	

According to the data obtained, it can be calculated that the burning of 1 ton of vegetable raw materials (straw residues) corresponds to the burning of 424 m^3 of natural gas — a non-renewable fossil fuel. The authors recalculated into energy units based on carbon dioxide emission coefficients for different types of fuel burned (Table 10).

Combustion should be taken into account that the incineration of agricultural waste gives zero GWP, since the CO_2 that entered the air during combustion was previously absorbed from the atmosphere during growth.

Another possible method of processing agricultural waste is anaerobic digestion. This process is a reduction in the initial volume of waste using biological processing in an airless space, followed by the formation of biogas. Anaerobic digestion is often associated with the recovery of methane (CH_4) and combustion for energy.

Thus, for 200 million tons of agricultural waste, there are 1,739.7 mln MWh / year of clean energy (taking into account the maintenance of the complex itself with heat and electricity, as well as the possibility of selling to the consumer). The average output of the CHP is about 3.5 billion kWh per year [44]. Consequently, the values of electricity generation are 4 times less at the biocomplex, however, plant raw materials, not fossil fuels, participate in energy generation, which makes it possible to use the volume of agricultural raw materials waste to a large extent. The results of the calculations showed that the most energy-efficient methods are the burning of fuel brackets of waste (about 152 PWh/year), as well as the generation of biofuels (1740 GWh/year).

At the same time, it has been shown that catalytic additives can be additionally used and this has a positive effect on the combustion process, as well as reduces emissions of pollutants [45]. The authors of the study calculated that the use of the proposed catalytic additives (CaO and $KMnO_4$) significantly increases the average temperature in the combustion chamber, makes the process more efficient and more complete with a reduction in carbon monoxide emissions. In the best case scenario, adding CaO reduced CO emissions by 41%, and similarly adding $KMnO_4$ to biomass pellets reduced CO emissions by 45%.

Another example of recycling is the production of biochar from agricultural waste. Consider one of the many examples. Thus, the technology of microwave torrefaction is a new method of heating the organic mass, which allows heat to evenly penetrate into the raw material [46].

Straw, manure and other agricultural waste processed using torrefaction processes can be used as raw materials for the production of bio-coal. In turn, various types of bio-coal have a wide range of applications, ranging from remediation of contaminated soils to the creation of new fertilizers based on it. This seems to be an energy-efficient method of reducing GHG emissions.

Table 10. Comparative assessment of CO_2 emissions from the combustion of natural gas and vegetable raw materials, taking into account emission factors (based on [43])

Таблица 10. Сравнительная оценка выбросов CO_2 при сжигании природного газа и растительного сырья с учетом коэффициентов выбросов (на основе [43])

	Amount of waste, t	Natural gas, m^3
Unit of measurement	1	424
CO_2 emission factor (t/unit)	100	54.4
Total amount of CO_2 emissions, t	100	23 065

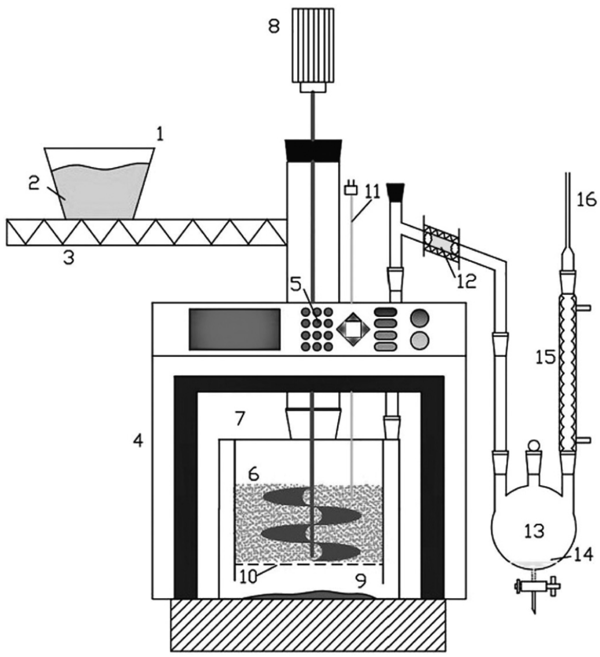

Figure1. Schematic diagram of microwave-assisted torrefaction system [50]

Рис. 1. Принципиальная схема системы торрефикации с использованием микроволновой печи [50]

A typical experimental system for microwave torrefaction is shown in Fig. 1. The system includes a microwave oven, a reactor, a condenser, a feeder, a gas supply device, a thermocouple and a liquid fractionator [47]. Before starting the process, the feedstock is added to the reactor, through which a carrier gas is blown to remove air from the device. In other modifications, the inert gas purges pyrolysis steam into the gas condenser. The process is easily controlled and does not require mixing or fluidization devices. In conclusion, the microwave torrefaction technology has high scalability and is suitable for processing many types of biomass in large volumes [48, 49].

5. Discussion

Agricultural productivity is based on the process of photosynthesis, which forms the primary products. In the agricultural production sector, it is believed that a combination of technologies to reduce emissions and increase carbon storage in the soil can allow this sector to achieve net negative emissions while maintaining high productivity. However, it has been established that agroecosystems are a net source of emitted GHGs [51]. Modern agricultural technologies for cultivating row crops are responsible for about 5% of greenhouse gas emissions in the United States and the European Union. In a number of countries (Russia, China, India, etc.), at present these values are even higher. In order to reduce GHG emissions, significant efforts are focused on the introduction of such techniques as 0-tillage, the introduction of large doses of organic and "green" fertilizers, in general, on the transition to organic low-carbon farming. At the same time, the potential for reducing emissions was largely neglected. Energy efficiency has also not always been considered as a key GHG emission management process. According to estimates [52], as well as other researchers [53—57], due to a combination of innovations in digital agriculture, crop genetics and microbes, as well as reclamation, it is possible to reduce greenhouse gas emissions by 71% (1744 kg CO_2-eq./ha) when growing row crops over the next 15 years (Fig. 2).

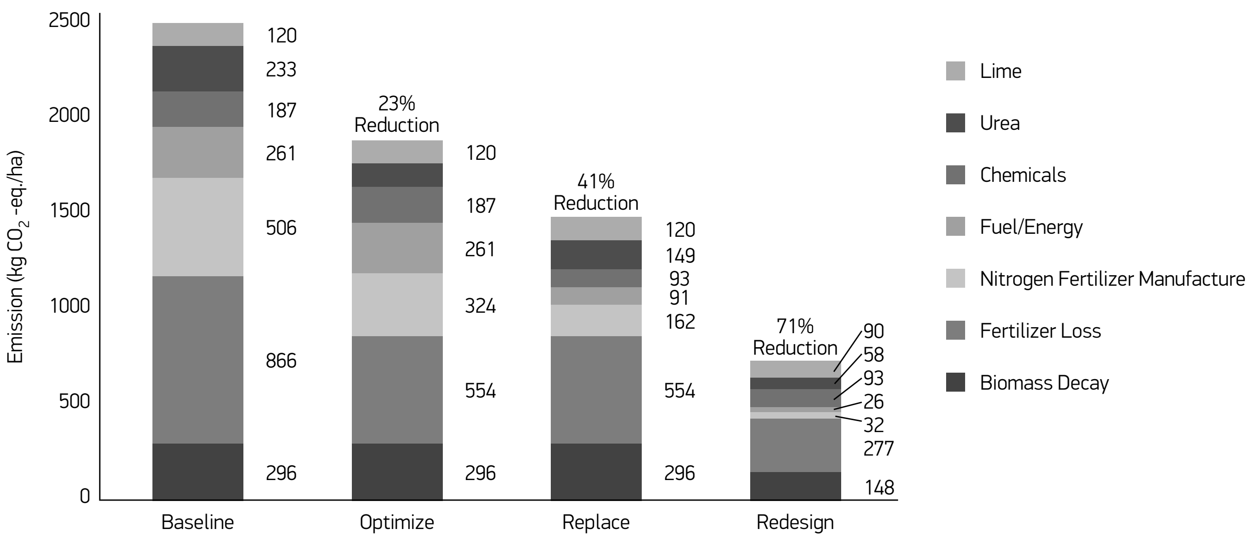

Figure 2. Technical improvements facilitate deep decarbonization of grain production. Numbers are shown as kilograms of CO_2-eq. per hectare and are separated by the emission source. The phases (optimize, replace, and redesign) are distinguished by the technical readiness of the enabling innovations. Implementing the optimization phase is largely possible using current technology, while replacement-phase technologies could be available in 2 to 5 y. and redesign-phase technologies in 5 to 15 y. [52]

Рис. 2. Технические усовершенствования способствуют глубокой декарбонизации производства зерна. Цифры указаны в килограммах CO_2-экв. на гектар и разделены источником выбросов. Этапы (оптимизация, замена и редизайн) отличаются технической готовностью внедряемых инноваций. Реализация фазы оптимизации в значительной степени возможна с использованием современных технологий, в то время как технологии фазы замены могут быть доступны через 2—5 лет, а технологии фазы редизайна — через 5—15 лет [52]

It is important to emphasize that the increase in energy efficiency values will be accompanied by a reduction in GHG emissions. Such a strategy can lower the barrier to widespread adoption by going through several stages with significant improvements. Ultimately, this will help agriculture to maintain its most important social function of providing society with food, while at the same time bringing environmental benefits.

One of the most important practices of implementing this approach is the production and widespread use of the necessary range of complex fertilizers for agriculture [58]. The main advantages of the new forms of complex fertilizers are, first of all, in the balance of mineral nutrition of plants, which is very difficult to ensure when using simple, standard forms of mineral fertilizers. Secondly, energy consumption is reduced by 65—70% for application to the soil by reducing the passage of technical means through the field. This is especially true in the spring, because at the same time, the overcompaction of the soil, which inevitably occurs when using energy-saturated tractors and fertilizer machines, is significantly reduced. In addition, a higher uniformity of fertilizer distribution over the soil surface is provided, which provides better conditions for mineral nutrition of plants. The transition to the use in the agricultural sector of agriculture for the large-scale use of new forms of complex mineral fertilizers will bring the crop industry of agriculture to a new, higher and qualitative level of development and will ensure further increase in crop productivity without increasing the overall need for fertilizers. An important factor in this case is to increase the energy efficiency of agroecosystems as a whole.

At the same time, the fundamental strategy for conducting research on carbon dioxide emissions as a measure of energy efficiency at all stages for the fertilizer system "production — logistic — application in croplands - waste utilization" is to assess the life cycle of both energy and GHG emissions (Fig. 3).

Let's consider the life cycle and coefficients of GHG emissions and the use of various energy sources in the "production — logistic — application in croplands - waste utilization" system. So, based on the data [59], for every ton of nitrogen produced and used on arable land in China, both as part of simple fertilizers (urea) and complex ones (for example, diammophos, an average of 13.5 tons of CO_2 equivalent (t CO_2-eq.) is emitted. At the same time, the highest values of GHG emissions are observed in the technological processes of ammonia synthesis. This is due to the energy-intensive nature of the process of production of mineral fertilizers, as well as in general with the chemical industry, where technological processes require high temperatures and pressures. In addition, the energy intensity of the initial heat sources is important. For example, coal, used in a number of countries as the main source of energy, has low energy efficiency. Coal-fired plants have an emission factor of > 5 t CO_2-eq. t NH_3-N^{-1} compared to < 3 t CO_2-eq. t NH_3-N^{-1} for natural gas plants [60—63]. The scale of production also matters. For example, when using the same energy source, large-scale installations emit slightly less GHG per unit N than medium- or small-scale installations. The next stage includes the "fertilizer production" block, aimed at converting ammonia and phosphates into various N-P fertilizers; the processes have a weighted emission factor of 0.9 t CO_2-eq. t N^{-1}, but a wide range from 0.3 to >6 t CO_2-eq. t N^{-1} (see, for example, [64, 1]).

Even in modern conditions, coal provides 86% of the energy consumed in the above processes. Methane emissions associated with coal mining have a global warming effect of 11.4 g CO_2-eq. MJ^{-1} (10^6 J) compared to < 2 g CO_2-eq. MJ^{-1} when using natural gas or oil [65,62].

The weighted emission factor can be 2.2 tons of CO_2-eq. t^{-1} fertilizers in the extraction and transportation of fossil fuels used in the fertilizer industry (including 1.8 tons of CO_2-eq. t N^{-1} from the extraction of energy used for the synthesis of ammonia, and 0.4 tons of CO_2-eq. t^{-1} when it is used for the production of, for example, N-P fertilizers). For the conditions of China, this is 16% of the total emissions of 13.5 tons of CO_2-eq. t N^{-1} [62]. Taking into account different sources of raw materials, these values can vary widely — < 1 ≥ 12 tons of CO_2-eq. per ton of fertilizers produced and used.

In the logistics process and during the transportation of nitrogen and phosphorus fertilizers, the emission coefficients are on average 0.1 t CO_2-eq. t^{-1}. (the range of values from < 0.05 ≥ 0.25).

Estimates of GHG emissions from growing crops vary significantly (< 2 ≥ 9 t CO_2-eq. t N^{-1}). Thus, the size of nitrogen denitrification can be in the wide range from 5 to 90% (averaged at 25—30%) of the mineral nitrogen content in the soils of agroecosystems [66]. Ammonia emissions on alkaline soils, the amount of nitrate leaching and the amount of dry and wet precipitation also vary significantly. For the conditions of China, the emission

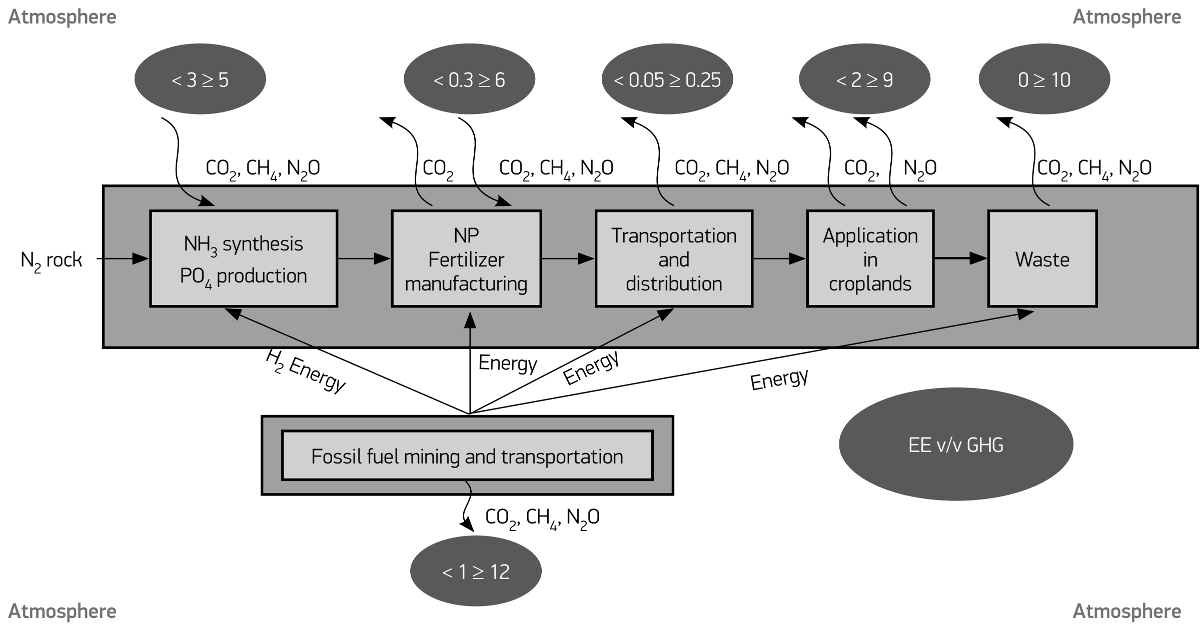

Figure 3. Assessment of the life cycle of greenhouse gas emissions from the production and use of nitrogen and phosphorus fertilizers and weighted emission factors for the main processes (explanations are given in the main text). Atmospheric nitrogen (N_2) combines with hydrogen using energy derived from fossil fuels. The resulting NH_3 reacts with CO_2, nitric acid, hydrochloric acid or phosphoric acid to produce various fertilizers. These fertilizers are transported in various ways before being applied to arable land. The solid line represents the consumption of materials and N fertilizers. The dotted line represents the exchange of GHG between the chain of production and use of fertilizers, including processing of agricultural waste, and the atmosphere

Рис. 3. Оценка жизненного цикла выбросов парниковых газов при производстве и использовании азотных и фосфорных удобрений и взвешенные коэффициенты выбросов для основных процессов (пояснения даны в основном тексте). Атмосферный азот (N_2) соединяется с водородом, используя энергию, получаемую из ископаемого топлива. Полученный NH_3 вступает в реакцию с CO_2, азотной кислотой, соляной кислотой или фосфорной кислотой с получением различных удобрений. Эти удобрения транспортируются различными способами перед внесением на пахотные земли. Сплошная линия представляет расход материалов и N удобрений. Пунктирная линия представляет собой обмен ПГ между цепочкой производства и использования удобрений, включая переработку сельскохозяйственных отходов, и атмосферой

coefficients are 5.2 t CO_2-eq. t N^{-1}, including direct emissions of N_2O (4.3 t CO_2-eq. N^{-1}) as a result of nitrification and denitrification in the soil and indirect emissions (0.9 tons of CO_2 equivalent per ton of nitrogen) [62].

At the end of the chain are greenhouse gas emissions from the processing and/or use of agricultural waste. As noted above, waste processing is significantly affected by the technological processes used, which have a very large variation in the values of their energy efficiency. This also affects the values of relative GHG emissions (from practically no to high values, see Fig. 3).

Consequently, the GHG emission values are a measure of energy efficiency in the "production — logistic — application in croplands — waste utilization" system.

Conclusions

In the context of global climate change and taking into account the increase in anthropogenic greenhouse gas emissions, the sustainability of agricultural systems can be improved by increasing the efficiency of energy use. Various agrotechnological techniques for reducing GHG emissions and increasing carbon sequestration are considered. At the same time, the potential for reducing emissions was largely neglected. Energy efficiency has also not always been considered as a key GHG emission management process.

The materials presented in this article testify to the key role of energy efficiency throughout the entire life cycle in the "production — logistic — application in croplands — waste utilization" system. The values of GHG emissions at the same time act only as a measure of this energy efficiency. Further, the processing of agro-industrial waste and raw materials using various processes (composting, bioenergy production, bio-coal, biogeochemical recycling of nutrients) can also significantly reduce GHG emissions. However, it can also potentially lead to greenhouse gas emissions as a result of composting and material transportation processes. Moreover, these processes have a positive effect both directly, due to carbon sequestration, and indirectly by preventing the consequences of waste disposal, improving soil quality and minimizing soil losses.

In general, an increase in energy efficiency in the considered life cycle of fertilizers, from production to utilization of agricultural waste, can significantly reduce the role of agricultural production in undesirable GHG emissions. It should be emphasized that reducing the potential of GHG emissions in the production of fertilizers depends on the source of energy used and the transfer of power plants from coal to gas, and especially RES, will be the most significant. When growing products, factors related to the use of modern farming systems based on accurate fertilization, the use of electronic soil maps, precision farming and increasing the efficiency of fertilizer use, in particular, nitrogen and phosphorus, play a very important role.

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Authors

Bashkin Vladimir N.: Doctor of Biological Sciences, Professor, Chief Researcher of the Institute of Physico-Chemical and iological Problems of Soil Science of the Russian Academy of Sciences
Number of publications: more than 400
Research interests: geoecological risks, gas industry, biogeochemistry
ResearcherID: J-4621-2018
Scopus Author ID: 7005340339
Contact information:
Address: Institutskaya str., 2, Pushchino, Moscow region, 142290, Russia
vladimirbashkin@yandex.ru

Alekseev Andrey O.: Corresponding Member of the Russian Academy of Sciences, Doctor of Biological Sciences, Chief Researcher, Head of the Department, Head of the Institute of Physico-Chemical and Biological Problems of Soil Science of the Russian Academy of Sciences
Number of publications: about 200
Research interests: soil science, soil mineralogy, biogeochemistry, geochemistry, environmental magnetism, soil organic matter, soil evolution, paleosols, paleogeography, Pleistocene, Holocene, Paleozoic
Scopus ID: 7202889447
ResearcherID: L-1162-2014
ORCID: 0000-0001-5158-4454
AuthorID: 58747
Contact information:
Address: Institutskaya str., 2, Pushchino, Moscow region, 142290, Russia
alekseev@issp.serpukhov.su

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