ENERGY CROPS – OUTLOOK FOR ENVIRONMENTAL FUTURE FOR HUMANITY AND THE PLANET EARTH

Mila Dobromirova Kaleva

The Stephan Angeloff Institute of Microbiology, Bulgarian Academy of Sciences, Sofia, Bulgaria

Abstract. The growing risk of irreversible depletion of fossil energy sources like petrol, natural gas and coal, and the emissions of gasses consequence from their combustion, is causing the necessity of the introduction of energy crops for the manufacture of energy products. These include annual or perennial plants, fast-growing tree types – hybrid willows, poplars and others, and water crops – red algae, giant kelp, seaweed etc. Most preferred in Europe and the US are *Paulownia sp.* (*P. elongata* и *P. tomentosa)*, giant reed (*Arundo donax*), elephant grass (*Miscanthus giganteus*), weeping willow (*Salix babylonica*) and wicker (*Salix viminalis*). So far in Bulgaria are preferred herbaceous energy crops such as corn, canola, sorghum, etc., but also were introduced some kind of timber. The global development of the sector would help to address the environmental problems associated with the release of huge quantities of greenhouse gasses. In the processing and utilization of energy crops, the amount of waste products is reduced to near zero, thereby avoiding environmental pollution.

Keywords: energy crops, *Paulownia* spp., *Salix* spp., *Arundo donax, Miscanthus giganteus*

INTRODUCTION

Energy crops represented a significant share of European and world agriculture. The production of biomass from these plants, grown on arable land has been an important part of the path to the large-scale development of renewable energy [101]. Among these types of crops, a particularly important place in the circular economy for obtaining energy from renewable energy sources was occupied by perennial grasses and trees. They significantly contribute to the fight against global climate change, and with high yields will guarantee energy security. At the end of the 20th century, [84] and [58] were announced that energy crops were suitable for growing in countries with a tendency for high energy consumption, high prices of other energy sources and in countries with many uncultivable agricultural areas, as well as areas not subject to cultivation and cultivation of other crops [90].

The use of renewable energy sources has been a possible solution to reduce emissions of harmful gasses from human activities that cause climate change. Also, the production of biogas has been generating a much lower amount of harmful gas emissions in the environment than the extraction and exploitation of other types of fuels. [40] were presented with a new technology for biomethane production from energy crops. According to them, the choice of crop depended mainly on the yield of biogas, the amount of readily available nitrogen in the secondary biomass and the type of agriculture in the respective area. The authors recommended growing winter and summer crops, choosing the most productive crops in terms of biogas yield, and using good agricultural practices and cultivation methods. Data indicate that as of 2019, 70% of the energy received for heating and electricity was from biomass of renewable energy plant sources [82].

Some of the plant species being used as energy crops are traditional agricultural crops applied in the food industry and animal husbandry, maize for example. Other plants of interest to scientists and experts were been tree and shrubby species, some of which were taken for granted in the surrounding environment. A suitable example of this was the representatives of the genus *Salix* (willows) and *Populus* (poplars), and others are perceived as weedy and invasive species – *Arundo donax*. The species from the genera *Miscanthus* and *Salix* are preferred over other perennial energy crops, as they have a high biomass yield, unaffected by the chemical composition of the soil [101].

[91] present perennial energy crops as a resource significantly more favourable to grow than annual plants, as they do not require additional fertilization or pesticide application to reach optimal growth and productivity.

Annually, energy crops participate with their biomass extremely little in the total energy production, but it is considered that in the next few decades, it would increase. The research of [77] highlights the advantages of energy crop utilization technologies and assesses their contribution to world energy and the prospects for use by the coming climate changes.

The text was aimed to highlight mostly the advantages, but also some disadvantages, of the considered energy crops. They has been easily accessible, undemanding and highly productive species, from which different vegetative parts a variety of environmentally friendly products are obtained – methane, ethanol, etc.

doi.org/10.32006/eeep.2024.1.1123
This article is lisensed under the Creative Commons Attribution 4.0 International License

TYPES OF PLANT ENERGY CROPS AND THEIR IMPORTANCE FOR METHANOGENESIS

MISCANTHUS GIGANTEUS KENG

The cultivation of elephant grass (*Miscanthus giganteus*) in Europe and North America began in the 1990s.That species is a perennial herbaceous crop from the *Poaceae* family. *Miscanthus giganteus* was distinguished by a high yield of cellulose-rich and caloric biomass [96], with a long growing season and development in warm seasons [62]. The main resources needed for this purpose are the availability of free cultivated area, water for irrigation, natural nutrients and suitable planting material. The production of *M. giganteus* lasts 15 – 20 years [101]. The final products from its processing are mainly wood and ethanol. According to their intended purpose, the latter has been used for heating, electricity generation and car fuel. Elephant grass has been considered the most suitable of the herbaceous perennial species to grow, as its propagation could be controlled by stem cuttings or rhizomes, which is an advantage. The research showed that rhizomes buried in the soil at a depth of 5 cm were developed best [107], and as a planting period favouring the development of the most abundant leaf mass was the second half of April [41].

In a comparative study with *Sida hermaphrodita* and *Arundo donax*, *Miscanthus giganteus* was presented with the highest dry matter content, the highest amount of heat released during combustion, methane and ethane production, better composition in terms of essential elements C, H, N, S [43].

Miscanthus giganteus is being yielded much higher biomass than wheat and soybean crops. Both economically and ecologically, it was shown more profitable than them. Its yield was from 20 to 26 tonnes per hectare (t ha^{-1}) per year [73]. They were found the highest productivity of this plant in the third year of its cultivation – 42.3 t ha^{-1} and was determined that the amount of cellulose and lignin was higher in the stems, and of hemicellulose and ash in the leaves [97]. In drier Mediterranean terrains, miscanthus performance is between 12,75 and 23,54 t ha^{-1} per year [57].when it has been the most favourable stage of the plant's vegetation, predisposing to efficient

A long-term study [20] recommended harvesting *M. giganteus* at the end of September preservation of lignocellulosic biomass during long-term storage. For successful implementation in energy production, this plant species must be maintained in extensive plantations in the long term [20]. [98] were reported that spring harvest yields were 18–31% lower than autumn harvest yields.

This energy crop has been shown to take in significantly more CO_2 through photosynthesis than it emits through combustion. It has high resistance against pests, therefore the use of harmful pesticides is unnecessary [19].

Miscanthus giganteus has long been an object of interest to scientists. [9] and [96] investigated its ability to extract phosphorus and heavy metals from soil. The authors compare it with other energy crops such as sorghum and switch grass (*Panicum virgatum*) proving that sorghum was extracted the greatest amount of phosphorus and sodium from the soil. These elements, however, changed the mineral composition of the biomass and subsequently negatively affected the pyrolysis process, as a result of which the yield of biogas has deteriorated.

[91] were compared the methane yield of *Miscanthus* and *Salix* species with that of maize. They were found that after pre-moistening with solutions of oxidants, causing changes in the lignocellulosic structure of the biomass and during anaerobic fermentation, a significantly larger amount of methane is produced than with corn. In comparison, untreated *Miscanthus* and *Salix* biomass was produced much less methane under anaerobic conditions than maize.

[11] were found that after mixing corn silage and *M. sacchariflorus* with pig manure in amounts of 7.5% and 12.5%, the most complete anaerobic digestion was achieved, with the biogas and methane yields being the highest.

[45] compared the prices of raw materials obtained in the cultivation of *M. giganteus*. The studied species were grown using MISCANMOD methods (a model related to the performance of *M. giganteus* based on the principles developed by Monteith [55]) and GIS (Geographic Information Systems), through which the yields of the two crops were evaluated. To create a viable bioenergy system, energy crops must be priced competitively with both forage crops and fuels. Arable land owners would be only started growing energy crops if they were sure that their profits would be close to those from the production of already established profitable agricultural crops.

In comparison with other energy crops (*Paulownia tomentosa*, *Salix viminalis*, *Populus euramericana*, *Sida Hermaphrodita*, *Arundo donax*, *Miscanthus giganteus)*, during combustion *Miscanthus giganteus* was showed the highest heat release value – 16,29 ± 0,14 MJ kg−1 [108].

As an alternative for ethanol production, the perennial species of the genera *Salix*, *Miscanthus, Populus* and representatives of the genus *Arundo* were suitable for cultivation due to their high yields and undemanding to the environment [102].

The high content of cellulose and hemicellulose in the leaves of *M. giganteus* could be used for conversion to cellulosic ethanol with high calorific value (18,5 MJ kg−1)[97].

ARUNDO DONAX LINNAEUS

Giant reed (*Arundo donax*) has been a herbaceous plant widely distributed in temperate and subtropical regions. It was classified in the family *Poaceae.* The exact origin of *A. donax* has been unclear. Evidence was suggested that the plant was cultivated and transported to Asia, southern Europe, northern Africa, the Middle East, and other locations about 5000 years ago [64]. *Arundo donax* has been a perennial plant and an alternative to the more familiar energy crops for biogas production [15]. *Arundo donax* was found to have favourable conditions for development even on eroded soils [26]. Giant reed has also been found to grow well on heavy metal (Cu, Zn and Cd) contaminated soils, where energy production could be combined with phytoremediation (the introduction of plants to treat soil and water contaminated with organic and inorganic pollutants) [7], [18], [95]. Cultivation of *A. donax* on such soils improves their quality indicators, by increasing the content of nitrogen and carbon in the soil layers, as well as improving the soil structure [23], [34]. Although *A. donax* was also grown in arid regions, in the presence of water the biomass obtained was significantly more. As an alternative to irrigation with fresh water, scientists have applied wastewater from treatment plants. They were found an increased yield, despite the lack of nitrogen fertilizers, soil enrichment and an increase in the amount of soil carbon [13].

Due to its ability to grow rapidly on infertile land, this species has been considered a dangerous weed [65], [69]. However, it is now spreaded all over the world because of its versatile application. Giant reed has being a raw material for the production of various high-value compounds, such as levulinic acid, oligosaccharides, fermentable sugars, highly digestible fibre for animal feed, polyphenols, and natural fibres for composite materials [65], [60].

Arundo donax has also been considered as a promising energy crop in recent years due to its high biomass yield, even higher than that of *M. giganteus* [27]. Genetic studies have shown a complex polyploid genome, which has made it difficult for scientists in their attempts to modify it in order to strengthen its positive qualities – productivity and resistance to adverse soil factors [17].

A. donax has been a plant that was propagated vegetatively by fragmentation of rhizomes or cuttings [65], therefore it is necessary to control and remove it from river basins [27] to prevent excessive and uncontrolled planting. The life span of the culture has been 12-15 years, which was the reason why there were also unclear facts about its cultivation and processing [65]. *Arundo donax* could be grown at a rate of 10 cm per day, which places it among the fastest growing plants known to mankind and could produce more than 20 tones of dry matter per hectare [64]. Data were indicated that the yield of *A. donax* per year is 54 t ha^{-1} [89].

As a storage method before the application of the biomass in bioreactors, it was studied the silage of *A. donax* in which fermentation was taken place with the separation of the organic acids malic and oxalic, from the decomposition of which volatile fatty acids were accumulated. The scientists have recommended two techniques. The resulting biomass from *A. donax* was found to give a good energy yield relative to the harvest period [15]. The fresh biomass obtained in autumn was subjected to anaerobic digestion, and the dry parts collected at the end of winter were subjected to pyrolysis [18]. Biomass from the winter harvest has been preferable, as it has reduced moisture, which has also facilitated its storage. The winter biomass of *A. donax* has also contained a reduced level of nitrogen that has passed back into the soil, thereby improving it for future crops and reducing the need for nitrogen fertilizers [23].

In Mediterranean regions, due to the long growing season from March to November, giant reed was characterized by high productivity [34].

In dry Mediterranean regions, giant reed could be produced an average biomass yield between 12.86 and 36.78 t ha^{-1} [57].

[72] were investigated the potential of A. donax as a feedstock for methane extraction according to the growth phase in which the biomass was harvested. Samples were taken at five different times of the year, and the scientists were found that methane yield was highest from young shoots.

[94] were studied the decomposition of *A. donax, Eucalyptus camaldulensis* and *Populus nigra*. They have proved that under normal (aerobic) conditions, bacteria were developed on the biomass of the studied plant species, contributing to the degradation of their lignocellulosic structure. The authors isolated 40 multienzyme bacterial strains from the phyla

Actinobacteria, Proteobacteria, Bacteroidetes and *Firmicutes*, and 62% of them were secreted the endo-1,4-ß-gluconase enzyme in a liquid medium extracellularly, accelerating the decomposition of plant biomass.

Australian scientists [99] have presented data from calculations that showed that 250 litres of ethanol could be produced from a ton of dry biomass of *A. donax*, with the degradation of sugars during biomass fermentation being 65%. The team's scientists aim to increase the breakdown of sugars to around 85% by applying different enzyme preparations, which would increased the ethanol yield by approximately 100 litres per ton. The energy produced from bioethanol derived from *A. donax* was about 28.1% of the total energy produced [10]. High ethanol yields were obtained from *A. donax* biomass was subjected to dilute acid pretreatment, under microaerophilic conditions and under the fermentative action of *Escherichia coli* MS04 [51].

SALIX VIMINALIS LINNAEUS

A shrubby representative of the *Salicaceae* family. Willow is considered a rapidly renewable resource, as its growth cycle is 3 – 5 years. For energy purposes, the shrub variety is preferred over the tree variety [87], [29], [36].

It was grown well on polluted soils, was accumulated heavy metals during its growth, which was preferable for energy plants [35]. Species of the genus *Salix* were suitable for phytoremediation, absorbing even cadmium from the soil [35], [46], [69], [81], but not lead [85]. Unlike coal, burning willow wood was not emit harmful gas emissions, the cause of the greenhouse effect [35]. There were studies through which it was established that *Salix viminalis* could be used for wastewater treatment. Through its root system, the plant was extracted harmful substances from the environment and was assimilated them to build biomass [19]. The development of willow massifs in areas close to domestic wastewater is recommended. However, as a means of purifying contaminated soils, *S. viminalis* was succeeding in extracting and assimilating nitrogen, but not chlorine, whose levels were critically elevated in arid regions [54]. The application of *S. viminalis* on coarse sand was investigated for the recovery of waste metabolites in sewage treatment plant waters. The efficiency of gravel alone was found to be: 45.7% for nitrogen, 85.8% for phosphorus, and 6.9% for potassium, and the plant increased this efficiency by up to 12% for nitrogen, by up to 5% for phosphorus and with up to 18% for potassium [52].

There was a problem in the purification of the waters in freshwater fishponds, related to the accumulation of large amounts of ammonia contained in the feces of fish. In Canada, a study was conducted in which it was proved that willow massifs could be intensively irrigated with water from fishponds, with ammonia and phosphorus have being maximally extracted from it [25].

Other studies were focused on the chemical composition of the plant species, namely the tannin content. Tannins are plant polyphenols that can have a positive effect on the physiological processes in the body of ruminants, their metabolism and the ruminal microflora [24]. Studies have used leaves from *Salix spp.*, known for their tannin content, on the other hand, willow leaves have had a high nutritional value and scientists were considered them as a good alternative to standard forage crops. [63] were found that tannins in the biomass of *S. viminalis* produced an inhibitory effect on some rumen microorganisms and on methanogenesis in general.

Data were indicated that the first crop of *Salix viminalis* '5027' was grown in a transition zone (a zone between agricultural and riparian areas) was 0.25 – 16.59 Mg ha−1 yr− [100].

As a result of the pyrolytic decomposition of lignin in woody biomass by S. viminalis, compounds with a benzene ring were formed. The formed organic chemical compounds could be used in the chemical industry and contributed to the promotion of the so called "green chemistry". 1,4-butanediol was one such compound. It is a valuable raw material for chemical synthesis (of tetrahydrofuran) and could be used as a solvent for plastics and paints [70].

Other analyses were shown, that during the process of burning *S. viminalis* biomass, 8 times less carbon monoxide and 6 times less sulfur dioxide were released into the atmosphere than when burning coal [79].

The autotetraploidy condition was observed in *S. viminalis* whose axial buds were treated with colchicine. This was led almost to the cessation of the growth of the plant, at the expense of an increase in its leaf mass, the diameter of the stems and the thickness of their bark. The leaf mass of these plants has higher levels of active gibberellins, cytokinins, salicylic acid and jasmonate. Due to the larger leaf area, photosynthesis and CO_2 uptake were increased [21].

Ethanol production was a direct dependence on the release of sugars in a given energy plant crop. [59] determined that the release of glucose and xylose was variable, even after pretreatment of *Salix viminalis* biomass, and was highly dependent on the phenotypic characteristics of the plant.

SALIX BABYLONICA LINNAEUS

Another widespread similar tree species from the *Salicaceae* family is the weeping willow (*Salix babylonica*). It is moisture-loving and grows mainly near ponds. A species adaptable to high temperatures [106]. Its wood was used for the production of furniture, and the substance salicyl was extracted from the bark of the young branches, which is a raw material for the production of aspirin [4]. *Salix spp*. were also involved in research in the field of veterinary medicine [30]. The choice of animal feed should be made by analyzing parameters such as digestibility, microbial protein production and last but not least, the release of gases into the environment. *S. babylonica* leaf mass has been found to provide quality nutrients to ruminants, but also the methane release produced in the gastrointestinal tract was inhibited during digestion and fermentation [14]. [71] were tracked the changes in haematological parameters in lambs whose daily ration was supplemented with an extract of *S. babylonica*. The obtained results were not shown changes in the studied indicators. On the other hand [92] were found that a combination of certain probiotics and *S. babylonica* extract applied in the daily diet of lambs were increased their appetite for feed, were improved nutrient digestibility through nitrogen utilization and microbial protein synthesis, resulting in increased daily gain. [74] have recommended the application of *S. babylonica* extract to the ratio of growing lambs, observing positive growth and no negative effects on animal health. [32] and [93] were made a comparative study of the anthelmintic activity of extracts of weeping willow (*S. babylonica*) and other plants – mimosa (*Leucaena leucocephal*a) and garlic (*Allium sativum*). *S. babylonica* extracts could be used as an alternative anthelmintic in small ruminants without compromising animal performance and rumen function.

[68] were conducted an *in vitro* study regarding the possible antimicrobial effect of aqueous extracts of dried leaves and twigs of *Salix babylonica* L. collected in spring and summer. The results were showed that the effect is stronger in aqueous extracts obtained from biomass collected in summer. The best results were obtained with *E. coli, S. enterica* and *C. albicans.*

In a study involving 13 plant species, S. babylonica were showed the lowest results in several indicators – total amount of gasses released, methanogenesis, percentage of methane and digestibility of organic matter. [53]

In vitro simulation of ruminal conditions were showed that S. babylonica in combination with exogenous fibrolytic enzymes (xylanase and cellulase) were increased the digestibility of organic matter, metabolizable energy and concentrations of short-chain fatty acids without changing the pH of the medium [75]. Salix babylonica is an energy plant crop suitable for implementation in phytoremediation processes [49], [50], [76], [86], [104].

Wastewater from the textile industry was subjected to electrochemical treatment, and subsequently through a hydroponic system were coming into contact with *S. babylonica*. Over half a month, water colour and turbidity were found to decrease by 85% and 93%, respectively [76].

The result of the experiment was showed that the powdered leaves of *S. babylonica* are a cheap and effective product for removing methylene blue from aqueous solutions by adsorption [42].

It has been found that aqueous extracts of weeping willow leaves and bark could be used as an effective and environmentally friendly biostimulant [56].

PAULOWNIA ELONGATA HU

Paulownia elongata is a perennial tree species of the family *Paulowniaceae* originating from China and also grown in Asia, USA, Australia and Europe. They were defined as the fastest-growing and highly productive trees in the world. In China and Japan since ancient times, therapeutic agents have been produced from various parts of the plant. The reporting of biomass productivity of the species were started to be reported after the second year. It could reach approximately 90 kg per year of wood, and dry biomass production could vary from 1.5 t ha^{-1} to 14 t ha^{-1}. Representatives of the genus *Paulownia* grow successfully on both polluted and eroded soil terrains [1], [37], [38], [44]. *Paulownia elongata* is a species suitable for phytoremediation and for inclusion in park and urban vegetation for air filtration in polluted urban conditions and control of CO_2 levels in atmospheric air [1], [28], [61], [83], [102]. Wood has had many uses, including as timber for construction, for making doors, furniture, kitchens, and more. Its cultivation has been economically very profitable, as it could be used in its entirety – from the root to the seed. It was used in traditional Chinese and Japanese medicine [12]. *Paulownia* trees produce several chemical compounds – verbascoside, diplacon, mimulon, apigenin, catalpol, aucubin and oleic acid, as well as some biologically active substances with antioxidant, anti-inflammatory and antibacterial effects [78].

Paulownia elongata leaves could be used as fodder for various farm animals [103], as they have a rich biochemical composition [109], a high content

of minerals and proteins, as well as exchangeable energy up to 18 MJ/kg [22]. Leaf biomass contains glutamic and aspartic acid, and essential amino acids [2]. In vivo, results were shown that adding up to 15% paulownia leaf meal instead of alfalfa hay in the ration of rabbits has had no negative effects on growth, nutrient digestibility and blood parameters. A reduced volume of the caecum and the number of forage pathogenic bacteria were also reported [6].

Paulownia biomass was a potential feedstock for hydrogen production by photofermentation. Different vegetative parts and varieties of genus *Paulownia* were shown different hydrogen productivity. The leaves of plants of the species were shown a better hydrogen production capacity [110].

In vitro was proved that aqueous extracts of leaves and silage of *P. elongata* exhibit an inhibitory effect on selected pathogenic microorganisms of the species *Salmonella enterica, Pseudomonas aeruginosa, Staphylococcus aureus, Streptococcus pyogenes, Paenibacillus alvei* and *Candida albicans*. They were proved that such extracts of leaves and silage of *P. elongata* were exhibited more pronounced antimicrobial effect on gram-negative bacteria [66].

Another study of theirs [67] was found that anaerobic digestion of *P. elongata* silage was produced a final biosludge with a very low content of microorganisms, which is particularly favourable from an ecological point of view. When studying silage and spring and autumn leaf mass from *P. elongata*, as well as other substrates (of plant origin, animal manure, sewage sludge). [80] proved increased biogas production in substrates with the participation of *P. elongata*.

[31] were presented results of an *in vitro* study of a mixture of rumen fluid with different conventional and alternative forage crops. Application of *P. elongata* leaves, under these conditions, were found a reduction in pH and methane emissions compared to *alfalfa* silage, as well as higher levels of *Fibrobacter succinogenes, Butyrivibrio fibrisolvens* and *Prevotella spp*., the total production of gas and total concentrations of volatile fatty acids, acetate and propionate were also higher.

[48] were determined that energy crops such as willow, sugar beet and grass silage placed under anaerobic conditions in two-stage fermenters yielded 5% more methane than crops placed under the same degradation conditions but in the laboratory. According to the authors, the better results were due to the two-stage fermenters maintaining good pH levels favouring hydrolysis in the two-stage system. The scientists were found that through this technology of processing energy crops, the heavy metals contained in the biomass were also successfully evacuated.

ENERGY CROPS IN DIFFERENT COUNTRIES OF THE WORLD

Chinese scientists were presented data obtained from three years of cultivation of *M. giganteus*, from which it was found that in the third year of the cultivation of the plant, its potential wass fully developed, namely 42.3 tons per hectare, gradually establishing it as an energy plant crop to promote bioenergy production in the country [97].

In 2012 [112] were claimed that in Poland by 2020, about 15% of the harvested energy would be from biomass of perennial energy crops, as the country has 1.59 million hectares of free arable land. The competitiveness of these crops is low compared to traditional and there is a high degree of risk associated with biomass production. The biomass prices vary but were warranted by profitability [112]. However, in 2021 [8] were published data showing that only about 3% of the produced energy was of biogas sources.

An 11-year experiment with *M. giganteus* and *M. sacchariflorus* (Amur silver grass) was made in North-Eastern Poland. Fresh mass yield of Amur silvergrass was between 31%–62% higher in the first 2 years of the experiment. However, in the third year, *M. giganteus* exceeded the yield of *M. sacchariflorus* by 1.7 to 3.7 times, and this growth in yield but fresh mass was maintained until the sixth year of the experiment [20].

In the state of Illinois, USA [62], it was reported that harvesting biomass of *M. giganteus* between August and November provided significantly more biomass than harvesting biomass after it was already overripe. Earlier harvesting, however, was reduced biomass yields in subsequent years. Nitrogen fertilization was compensated to some extent for yield losses. On the other hand, harvesting after aging was optimised the crop's long-term productivity, reducing the need for fertilization.

In the last decade, the scarce agricultural land in the Berlin-Brandenburg area, Germany has been negatively impacted by the continuous and monoculture cultivation of maize as a product for biogas production. Due to this fact, the fertile land in the region was subjected to soil degradation and the environment was devoided of species diversity. *M. giganteus* was preferred as an alternative plant crop, with a high yield of biomass, biogas and low requirements for the chemical composition of the soil [88].

The suitable soil-climatic conditions in Ukraine favour the cultivation of *M. giganteus* with a high level of energy accumulation in biomass during the growing season. Another success factor in this geographical area was the long period for photosynthesis – from early spring to late autumn [41].

In 2009, in Serbia [84] were conducted biomonitoring of soil and atmosphere, comparing the accumulation of the heavy metals – nickel and lead in the leaves of *P. elongata* S. Y. Hu and *P. fortunei* Hemsley, grown under urban and non-urban conditions. The plants were grown in the cities took up twice as much nickel as the plants in the experimental non-urban field. The authors recommend *P. elongata* have beeen grown in urban settings – parks, alleys, and road arteries as an air-purifying plant.

LIMITATIONS AND DISADVANTAGES OF ENERGY CROPS

[3] were compared the production of biogas and biodiesel from energy crops and the environmental effects thereof. They has refuted the accepted notion that the cultivation of energy crops is suitable for the utilization of already uncultivable areas, indicating that for this purpose a change in the use of lands in these areas was necessary. Land reclamation for food crops or other bioenergy crops was also a complicating factor[105], [111]. A serious disadvantage of growing these crops is the need for irrigation, which would change the hydrological situation in the region of their cultivation. The authors was also emphasized the positive effect of biogas production, namely the use of biosludge as a fertilizer obtained as one of the end products of methanogenesis.

Growing annual energy crops were provided a potential alternative for farmers to convert their arable land into more profitable pieces of land. This would significantly reduced yields of forage varieties and crops for the food industry. Another disadvantage of these crops was their need for additional amounts of nitrogenous compounds necessary to develop their full potential [101].

A disadvantage of *M. giganteus* was the fact that it has been a very moisture-loving plant and cultivation in large massifs has been creating a danger of changes in the hydrological situation in the given area [31]. A disadvantage of the biomass obtained from the representatives of the genera *Miscanthus* and *Salix* was the hard lignocellulosic structure. For this reason, [39] pre-treated the biomass with an ammonia solution before introducing it into the bioreactor. After such treatment, methane production was increased by 25-27% for *Miscanthus* and by 94-162% for *Salix*.

Arundo donax was shown comparable yields to *M. giganteus* in bioenergy production but required more energy input for planting. Giant reed was more invasive than elephant grass, which necessitates ecological control – prevention of flooding in growing areas, control of soil nutrients [27].

The question of how justified the cultivation of *A. donax* was debated, since it has been established that due to the rapid growth rate, its spread has become uncontrollable and necessitates the possible use of herbicides, which will make production more expensive and contribute to significant environmental pollution environment [65].

CONCLUSIONS

Worldwide scientific research has been presented the need to use energy crops as an ecological and efficient option for energy production. That was why these cultures are becoming popular in the world and in our country. In Bulgaria, annual plants such as corn, sugar beet, fodder and red beet were still used as such.

Considerable attention should be paid to the optimization of the cultivation of new energy crops, their popularization among agricultural producers and the introduction of biofuels as a modern adequate source of energy.

Miscanthus giganteus is an economically and ecologically beneficial energy crop. It is characterised by a much higher biomass yield than wheat crops and soybeans, high resistance against pests and elimination of harmful pesticides, as well as a high degree of CO_2 absorption during photosynthesis. *Arundo donax* is perfect for phytoremediation and also as a complementary feedstock to bioreactors to increase methanogenesis. Representatives of the genus *Salix* are of interest to scientists, as they are widely used in various fields of production. S*alix viminalis* can be applied near polluted bodies of water, and *Salix babylonica* – from the woodworking industry, through microbiology to veterinary medicine. *Paulownia* trees produce some biologically active substances, and in particular *P. elongata* exhibits an inhibitory effect on selected pathogenic microorganisms.

REFERENCES

1. Boyadzhieva, G., B. Baĭkov, Ekologichna otsenka na energiĭnata kultura Paulovniya v Bŭlgariya, Ekologizatsiya, Nov bŭlgarski universitet, 2012, 34-39.

2. Koleva, A., K. Dobreva, M. Stoyanova, P. Denev, S. Damyanova, A. Ilchev, S. Tasheva, G. Ganchev, D. Pavlov, B. Angelov, A. Stoyanova, 2011, Paulovniya, izv. na biologichno aktivni veshtestva. 1. Sŭstav na lista. 2. Aminokiselinen sŭstav na listata. Spisanie za planinsko zemedelie na Balkanite. 14, 5, 1061-1086.

3. Staĭkova, Y. U., B. Baĭkov, Prilozhenie na kriterii za sravnitelna otsenka pri proizvodstvoto na biogaz i biodizel ot energiĭni kulturi, Nov bŭlgarski universitet, Ekologizatsiya, 2012, 180-189.

4. Tonkov, S. i dr., Sistematika na visshite rasteniya. Sofiya-Moskva, Pensoft, 2005, 175-177.

5. Allen, B., B. Kretschmer, D. Baldock, H. Menadue, S. Nanni, G. Tucker, Space for energy crops – assessing the potential contribution to Europe's energy future, IIEP, 2014, 1-64.

6. Al-Sagheer, A. A., Abd El-Hack, M. E., Alagawany, M., Naiel, M. A., Mahgoub, S. A., Badr, M. M., & Swelum, A. A. Paulownia leaves as a new feed resource: Chemical composition and effects on growth, carcasses, digestibility, blood biochemistry, and intestinal bacterial populations of growing rabbits. *Animals*, 9(3), 2019, 95.

7. Arthur, E. L., Rice, P. J., Rice, P. J., Anderson, T. A., Baladi, S. M., Henderson, K. L., Coats, J. R. Phytoremediation—an overview. *Critical Reviews in Plant Sciences*, *24*(2), 2005, 109-122.

8. Bielski, S., Marks-Bielska, R., Zielińska-Chmielewska, A., Romaneckas, K., Šarauskis, E. Importance of agriculture in creating energy security—A case study of Poland. *Energies*, *14*(9), 2021, 2465.

9. Boateng, A. A., M. J. Serapiglia, C. A. Mullen, B. S. Dien, F. M. Hashem, R. B. Dadson, Bioenergy crops grown for hyperaccumulation of phosphorous in the Delmarva Peninsula and their biofuels potential, Journal of Environmental Management, 150, 2015, 39-47.

10. Brusca, S., Cosentino, S. L., Famoso, F., Lanzafame, R., Mauro, S., Messina, M., Scandura, P. F. . Second generation bioethanol production from *Arundo donax* biomass: an optimization method. *Energy Procedia*, *148*, 2018, 728-735.

11. Bułkowska, K., T. Pokó, E. Klimiuk, Z. M. Gusiatin, Optimization of anaerobic digestion of a mixture of *Zea mays* and *Miscanthus sacchariflorus* silages with various pig manure dosages, Bioresource Technology, 125, 2012, 208-216.

12. Buzan, R. L., Maxim, A., Odagiu, A., Balint, C., HARTAGAN, R. M. *Paulownia* sp. used as an energetic plant, for the phytoremediation of soils and in agroforestry systems. *ProEnvironment Promediu*, *11*(34), (2018).

13. Cano-Ruiz, J., Fernández, J. R., Alonso, J., Mauri, P. V., & Lobo, M. C. Value-added products from wastewater reduce irrigation needs of *Arundo donax* energy crop. *Chemosphere*, *285*, 2021, 131485.

14. Cengiz, T., Kamalak, A. Determination of potential nutritive values and anti-methanogenic characteristics of *Salix babylonica* leaves grown in different sites., *KSÜ Tarim ve Doga Dergisi*, 23, 5, 2020, 1351-1358.

15. Corno, L., Pilu, R., Cantaluppi, E., & Adani, F. Giant cane (*Arundo donax* L.) for biogas production: The effect of two ensilage methods on biomass characteristics and biogas potential. *Biomass and Bioenergy*, *93*, 2016, 131-136.

16. Csurhes, S., Pest weed risk assessment: Giant reed *Arundo donax*, Queensland Primary Industries and Fisheries, 2009, 7–14.

17. Danelli, T., Laura, M., Savona, M., Landoni, M., Adani, F., Pilu, R. Genetic improvement of *Arundo donax* L.: Opportunities and challenges. *Plants*, *9*(11), 2020, 1584.

18. Danelli, T., Sepulcri, A., Masetti, G., Colombo, F., Sangiorgio, S., Cassani, E., Anelli, S., Adani, F., Pilu, R. *Arundo donax* L. biomass production in a polluted area: Effects of two harvest timings on heavy metals uptake. *Applied Sciences*, *11*(3), 2021,1147.

19. Drożyner, P., W. Rejmer, P. Starowicz, A. Klasa, K. A. Skibniewska, Biomass as a renewable source of energy, Technical Sciences, 16, 3, 2013, 211-220.

20. Dubis, B., Jankowski, K. J., Załuski, D., Bórawski, P., Szempliński, W. Biomass production and energy balance of *Miscanthus* over a period of 11 years: A case study in a large‐scale farm in Poland. *Gcb Bioenergy*, *11*(10), 2019, 1187-1201.

21. Dudits, D., Török, K., Cseri, A., Paul, K., Nagy, A. V., Nagy, B., Sass, L., Ferenc G., Vankova, R., Dobrev, P., Vass, I., Ayaydin, F. Response of organ structure and physiology to autotetraploidization in early development of energy willow *Salix viminalis*. *Plant Physiology*, *170*(3), 2016, 1504-1523.

22. El-Showk, S., N. El-Showk, The paulownia tree – an alternative for sustainable forestry. The farm., 2003, 1-8.

23. Fagnano, M., Impagliazzo, A., Mori, M., Fiorentino, N. Agronomic and environmental impacts of giant reed (*Arundo donax* L.): results from a long-term field experiment in hilly areas subject to soil erosion. *Bioenergy Research*, *8*, 2015, 415-422.

24. Falchero, L., R.H. Brown, I. Mueller-Harvey, S. Hanley, I. Shield, A. Karp, Condensed tannins in willow (*Salix* spp.): a first step to evaluate novel feeds for nutritionally improved animal products, Grassland Science in Europe, 16, 2011, 434-436.

25. Fillion, M., J. Brisson, T.I. Teodorescu, S. Sauve, M. Labrecque, Performance of *Salix viminalis* and *Populus nigra* x *Populus maximowiczii* in short rotation intensive culture under high irrigation. Biomass and Bioenergy, 33, 2009, 1271-1277.

26. Forte, A., Zucaro, A., Faugno, S., Basosi, R., Fierro, A. Carbon footprint and fossil energy consumption of bio-ethanol fuel production from *Arundo donax* L. crops on marginal lands of Southern Italy. *Energy*, *150*, 2018, 222-235.

27. Ge, X., Xu, F., Vasco-Correa, J., Li, Y. Giant reed: A competitive energy crop in comparison with miscanthus. *Renewable and Sustainable Energy Reviews*, *54*, 2016, 350-362.

28. Ghazzawy, H. S., Bakr, A., Mansour, A. T., Ashour, M. *Paulownia* trees as a sustainable solution for CO_2 mitigation: assessing progress toward 2050 climate goals. *Frontiers in Environmental Science*, *12*, 2024, 1307840.

29. Grîu, T., & Lunguleasa, A. *Salix viminalis* vs. *Fagus sylvatica*-fight for renewable energy from woody biomass in Romania. *Environmental Engineering & Management Journal (EEMJ)*, *15*(2),2016 .

30. Haj-Zaroubi, M., Mattar, N., Awabdeh, S., Sweidan, R., Markovics, A., Klein, J. D., Azaizeh, H. Willow (*Salix acmophylla*) Leaf and Branch Extracts Inhibit *In Vitro* Sporulation of Coccidia (*Eimeria spp*.) from Goats, 2024.

31. Heaton, E., A. Frank, G. Dohleman, A. F. Miguez, J. A. Juvik, V. Lozovaya, J. Widholm O. A. Zabotina, G. F. Mcisaac, M. B. David, T. B. Voigt, N. N. Boersma S. P. Long, Miscanthus: A promising biomass crop, advances in botanical research, 56, 2010, 76.

32. Hernandez, P. M., A. Z. Salem, M. M. Elghandour, M. Cipriano-Salazar, B. Cruz-Lagunas, L.M. Camacho, Anthelmintic effects of *Salix babylonica* L. and Leucaena leucocephala Lam. extracts in growing lambs, Tropical Animal Health and Production, 46, 1, 2014, 173-178.

33. Huang, H., Szumacher-Strabel, M., Patra, A. K., Ślusarczyk, S., Lechniak, D., Vazirigohar, M., Varadyova, Z., Kozłowska, M., Cieślak, A. Chemical and phytochemical composition, in vitro ruminal fermentation, methane production, and nutrient degradability of fresh and ensiled Paulownia hybrid leaves. *Animal Feed Science and Technology*, *279*, 2021, 115038.

34. Impagliazzo, A., Mori, M., Fiorentino, N., Di Mola, I., Ottaiano, L., De Gianni, D., Nocerino, S., Fagnano, M. Crop growth analysis and yield of a lignocellulosic biomass crop (Arundo donax L.) in three marginal areas of Campania region. *Italian Journal of Agronomy*, *12*(1), 2017.

35. Jama, A., W. Nowak, Willow (*Salix viminalis* L.) in purifying sewage sludge treated soils. Polish Journal of Agronomy, 9, 2012, 3-6.

36. Jakubowski, W., Szulczewski, W., Żyromski, A., Biniak-Pieróg, M. The estimation of basket willow (Salix viminalis) yield–New approach, Part II: Theoretical model and its practical application. *Renewable and Sustainable Energy Reviews*, *66*, 2016, 843-851.

37. Jakubowski, M. Cultivation potential and uses of Paulownia wood: A review. *Forests*, *13*(5), 2022, 668.

38. Joshee, N., *Handbook of bioenergy crop plants*. CRC Press., 2012, 671-685.

39. Jurado, E., H. N. Gavala, I. V. Skiadas, Enhancement of methane yield from wheat straw, miscanthus and willow using aqueous ammonia soaking, Environmental Technology, 34, 13-16, 2013, 2069-2075.

40. Jury, C., E. Benetto, D. Koster, B. Schmitt, J. Welfring, Life Cycle Assessment of biogas production by monofermentation of energy crops and injection into the natural gas grid, Biomass and Bioenergy**,** 34, 1, 2010, 54–66.

41. Khakhula, V., Grabovskyi, M., Panchenko, T., Pravdyva, L., Fuchylo, Y., Kvak, V., Khakhula, B. Energy productivity of miscanthus giganteus depending on growing technology elements., 2020.

42. Khodabandehloo, A., Rahbar-Kelishami, A., Shayesteh, H. Methylene blue removal using *Salix babylonica* (Weeping willow) leaves powder as a low-cost biosorbent in batch mode: Kinetic, equilibrium, and thermodynamic studies. *Journal of Molecular Liquids*, *244*, 2017, 540-548.

43. Kron, I., Porvaz, P., Kráľová-Hricindová, A., Tóth, Š., Sarvaš, J., & Polák, M. Green harvests of three perennial energy crops and their chemical composition. *International Journal of Agriculture and Environmental Research*, *3*(2), 2017, 2870-2883.

44. Kole, C., Joshi, C. P., Shonnard, D. R. (Eds.). *Handbook of bioenergy crop plants*. CRC Press., 2012, 671-685.

45. Khanna, M., B. Dhungana, J. Clifton-Brown, Costs of producing miscanthus and switchgrass for bioenergy in Illinois, Biomass and Bioenergy, 32, 2008, 482 – 493.

46. Labrecque M., Teodorescu T.I., High biomass yield achieved by Salix clones in SRIC following two 3-year cop-pice rotations on abandoned farmland in southern Quebec, Canada. Biomass Bioenergy, 25, 2003,135-146.

47. Lee, Z. S., Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University, 2013.

48. Lehtomäki, A., L. Björnsson, Two-stage anaerobic digestion of energy crops: methane production, nitrogen mineralisation and heavy metal mobilisation, environmental Technology, 27, 2, 2006, 209-218.

49. Li, H., Zhang, G. C., Xie, H. C., Li, K., & Zhang, S. Y.. The effects of the phenol concentrations on photosynthetic parameters of Salix babylonica L. *Photosynthetica*, *53*, 2015, 430-435.

50. Li, K., Li, H., Li, C., Xie, H. Phytoremediation of aniline by Salix babylonica cuttings: removal, accumulation, and photosynthetic response. *Ecotoxicology and Environmental Safety*, *214*, 2021, 112-124.

51. Loaces, I., Schein, S., Noya, F. Ethanol production by Escherichia coli from *Arundo donax* biomass under SSF, SHF or CBP process configurations and in situ production of a multifunctional glucanase and xylanase. *Bioresource technology*, *224*, 2017, 307-313.

52. Mant, C., J. Peterkin, E. May, J. Butler, A feasibility study of *Salix viminalis* gravel hydroponic system to renovate primary settled wastewater, Bioresource Technology, 90, 2003, 19-25.

53. Mamhood Ameen, S. *Potential nutritive value and methane production of some ruminant feedstuffs from north of Iraq estimated using an in vitro gas technique* (Master's thesis, Fen Bilimleri Enstitüsü), 2015, 47-48.

54. Marmiroli, M., B.H. Robinson, B.E. Clothier, N.S. Bolan, N. Marmiroli, R. Schulin, Effect of dairy effluent on the biomass, transpiration, and elemental composition of *Salix kinuyanagi Kimura*. Biomass and Bioenergy 37, 2012, 282-288.

55. Monteith, J. L. Climate and the efficiency of crop production in Britain. *Philosophical transactions of the royal society of London. B, Biological Sciences*, *281*(980), 1977, 277-294.

56. Mutlu-Durak, H., Arikan, Y., Kutman, B. Y. Willow (*Salix babylonica*) Extracts Can Act as Biostimulants for Enhancing Salinity Tolerance of Maize Grown in Soilless Culture. *Plants*, *12*(4), 2023, 856.

57. Nazli, R. I., Tansi, V., Öztürk, H. H., Kusvuran, A. Miscanthus, switchgrass, giant reed, and bulbous canary grass as potential bioenergy crops in a semi-arid Mediterranean environment. *Industrial crops and products*, *125*, 2018, 9-23.

58. Nordberg, A., M. Edström, "Co-digestion of ley crop silage, source-sorted municipal solid waste and municipal sewage sludge." REUR Technical Series (FAO) 52, 1997.

59. Ohlsson, J. A., Hallingbäck, H. R., Jebrane, M., Harman-Ware, A. E., Shollenberger, T., Decker, S. R., Sandgren, M., Rönnberg-Wästljung, A. C. Genetic variation of biomass recalcitrance in a natural *Salix viminalis* (L.) population. *Biotechnology for biofuels*, *12*, 2019, 1-12.

60. Ortega, Z., Bolaji, I., Suárez, L., Cunningham, E. A review of the use of giant reed (*Arundo donax* L.) in the biorefineries context. *Reviews in Chemical Engineering*, (0), 2023.

61. Osmanović, Z., Huseinović, S., Bektić, S., Ahmetbegović, S. Construction of bioparks on devastated land in urban areas. *Periodicals of engineering and natural sciences*, *5*(1), 2017.

62. Parrish, A.S., Lee, MS., Voigt, T.B., Lee, D.K.. *Miscanthus x giganteus* Responses to Nitrogen Fertilization and Harvest Timing in Illinois, USA. *Bioenerg. Res.* 14, 2021, 1126–1135.

63. Pellikaan, W. F., Stringano, E., Leenaars, J., Bongers, D. J., Schuppen, S. V. L. V., Plant, J., Mueller-Harvey, I., Evaluating effects of tannins on extent and rate of in vitro gas and CH4 production using an automated pressure evaluation system (APES). Animal Feed Science and Technology, 166, 2011, 377-390.

64. Perdue, R. E., *Arundo donax*—Source of musical reeds and industrial cellulose, *Economic Botany*, 12, 1958, 368–404.

65. Pilu, R., A. Manca, M. Landoni, , *Arundo donax* as an energy crop: pros and cons of the utilization of this perennial plant, Maydica 58, 2013, 54-59.

66. Popova, T. P., Baykov, B. D. Antimicrobial activity of aqueous extracts of leaves and silage from *Paulownia elongata*. American Journal of Biological, Chemical and Pharmaceutical Sciences, 1, 2, 2013, 8 – 15.

67. Popova, T., Marinova, S., Zaharinov, B., Kaleva, M., Baykov, B., Kirov, V., Petrova, V. Reduction of sanitary indicator microorganisms in anaerobic digestion of poultry litter in combination with silages. International Symposium ISB-INMA TEH, Agricultural and Mechanical Engineering, ISSN 2344 – 4118, Bucharest, Romania, 2013, 245-252.

68. Popova, T. P., Kaleva, M. D. Antimicrobial effect in vitro of aqueous extracts of leaves and branches of willow (*Salix babylonica* L.). *Int. J. Curr. Microbiol. Appl. Sci*, *4*, 2015, 146-152.

69. Rodriguez, L. D., Confalone, A. E., Lazaro, L., Pimentel, R. M., Lyra, G. B., de Oliveira Júnior, J. F., Singh, S. K., Pereira, C. R. Growth of the energy crop giant reed (*Arundo donax* L.) and optimization of the ARMIDA model in the south-central region of Buenos Aires, Argentina. *Industrial Crops and Products*, *211*, 2024, 118190.

70. Roman, K., Roman, M., Szadkowska, D., Szadkowski, J., Grzegorzewska, E. Evaluation of physical and chemical parameters according to energetic willow (*Salix viminalis* L.) cultivation. *Energies*, 2021, *14*(10), 2968.

71. Rivero, N., A. Z. M. Salem, H. M. Gado, M. Gonzalez-Ronquillo, A. B. Pliego, C. G. Peñuelas, N. E. Odongo. Effect of exogenous enzymes and *Salix babylonica* extract or their combination on haematological parameters in growing lambs., Journal of Animal and Feed Sciences, 21, 2012, 577–586.

72. Ragaglini, G., F. Dragoni, M. Simone, E. Bonari, Suitability of giant reed (*Arundo donax L.*) for anaerobic digestion: effect of harvest time and frequency on the biomethane yield potential, Bioresourc Technology, 152, 2014, 107-115.

73. Qin, Z., Q. Zhuang, M. I. Chein, Impacts of land use change due to biofuel crops on carbon balance, bioenergy production, and agricultural yield, in the conterminous United States, GCB Bioenergy , 4, 2012, 277–288.

74. Salem, A. Z., Kholif, A. E., Olivares, M., Elghandour, M. M., Mellado, M., Arece, J. Influence of *S. babylonica* extract on feed intake, growth performance and diet in vitro gas production profile in young lambs. *Tropical Animal Health and Production*, *46*, 2014, 213-219.

75. Salem, A. Z., Buendía-Rodríguez, G., Elghandour, M. M., Berasain, M. A. M., Jiménez, F. J. P., Pliego, A. B., Chagoyán, J. C. V., Cerrillo, M. A. Rodríguez, M. A. Effects of cellulase and xylanase enzymes mixed with increasing doses of Salix babylonica extract on in vitro rumen gas production kinetics of a mixture of corn silage with concentrate. *Journal of Integrative Agriculture*, *14*(1), 2015, 131-139.

76. Sánchez-Sánchez, A., Tejocote-Pérez, M., Fuentes-Rivas, R. M., Linares-Hernández, I., Martínez-Miranda, V., Fonseca-Montes de Oca, R. M. G. Treatment of a textile effluent by electrochemical oxidation and coupled system electooxidation–Salix babylonica. *International Journal of Photoenergy*, *2018*.

77. Sims, R. E., Hastings, A., Schlamadinger, B., Taylor, G., Smith, P. Energy crops: current status and future prospects. *Global change biology*, *12*(11), 2006, 2054-2076.

78. Sławińska, N., Zając, J., & Olas, B. Paulownia Organs as Interesting New Sources of Bioactive Compounds. *International journal of molecular sciences*, *24*(2), 2023, 1676.

79. Sobczyk, W., & Sobczyk, E. J. Economical and ecological effects of cultivation of basket willow Salix viminalis L. In *IOP Conference Series: Earth and Environmental Science*, 214(1), 2019, 012002.

80. Shindarska, Z., B. Zaharinov, V. Petrova, P. Ivanov, G. Kostadinova, V. Kirov, B. Baykov, Ecological assessment of different raw materials for biogas, International Synposium ISB-INMA TEH, Agricultural and Mechanical Engineering, ISSN 2344 – 4118, Bucharest, Romania, 2013, 215-222.

81. Shield, I., Macalpine, W., Hanley, S., Karp, A. Breeding willow for short rotation coppice energy cropping. *Industrial crops: Breeding for bioenergy and bioproducts*, 2015, 67-80.

82. Słupska, M., Dyjakon, A., Stopa, R., Determination of Strength Properties of Energy Plants on the Example of *Miscanthus× Giganteus*, *Rosa Multiflora* and *Salix Viminalis*. *Energies*, *12*(19), 2019, 3660.

83. Stankovič, D., R. Igič, M. Šijaič-Nikolič, D. Vilotič, S. Pajevič,, Contents of the Heavy metals nikel and lead in leaves of *Paulownia elongata S. Y. Hu* and *Paulownia fortunei hems* in Serbia, Archives of Biological Science, Belgrade, 61, 4, 2009, 827-834.

84. Steffen, R., Szolar, O., Braun, R., Feedstocks for Anaerobic Digestion., Institute

for Agrobiotechnology Tulln University of Agricultural Sciences Vienna, 1998, 9-21.

85. SUBȚIRELU, V. R., COCÂRȚĂ, D. M., Badea, A. The Effect Of Sewage Sludge On Energy Willow (Salix Viminalis "Energo") Productivity, U.P.B. Sci. Bull., Series C, 79(2), 2017, 207-216.

86. Sun, C., Li, C., Mu, W., Ma, L., Xie, H., Xu, J. The photosynthetic physiological response and purification effect of Salix babylonica to 2, 4-dinitrophenol wastewater. *International Journal of Phytoremediation*, *24*(7), 2022, 675-683.

87. Tahvanainen, L., V. M. Rytkonen, Biomass production of *Salix viminalis* in southern Finland and the effect of soil properties and climate conditions on its production and survival. Biomass and Bioenergy 16, 1999, 103-117.

88. Tavakoli-Hashjini E, Piorr A, Müller K, Vicente-Vicente JL. Potential Bioenergy Production from *Miscanthus* × *giganteus* in Brandenburg: Producing Bioenergy and Fostering Other Ecosystem Services while Ensuring Food Self-Sufficiency in the Berlin-Brandenburg Region. *Sustainability*. 12(18), 2020,7731.

89. Tomàs, J., Mateu, J., Gil, L., Boira, H., Llorens, L. Arundo micrantha Lam. as an alternative to *Arundo donax* L. as energy crop in saline soils irrigated with treated urban wastewaters. *Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology*, *154*(4), 2020, 560-567.

90. Tulbure, M. G., Wimberly, M. C., Boe, A., Owens, V. O., Climatic and genetic controls of yields of switch grass, a model bioenergy species. *Agriculture, Ecosystems and Environment*, 146, 2012, 121–129.

91. Uellendahlm, H., Wang, G., Møller, H. B., Jørgensen, U., Skiadas, I. V., Gavala, H. N., Ahring, B. K. Energy balance and cost-benefit analysis of biogas production from perennial energy crops pretreated by wet oxidation. *Water science and technology*, *58*(9), 2008, 1841-1847.

92. Valdes, K. I., et al. Influence of exogenous enzymes in presence of *Salix babylonica* extract on digestibility, microbial protein synthesis and performance of lambs fed maize silage. *The Journal of Agricultural Science*, *153*(4), 2015, 732-742.

93. Vargas-Bello-Pérez, E., Ghavipanje, N., Gonzalez, T. T., Hernandez, J. C. A., Velázquez-Ordoñez, V., Ortega, O. A. C., Jimenez, L. E. R., Roskof, S., González-Ronquillo, M. Effect of calcium soaps from garlic and *Salix babylonica* extracts on nematode loads, nutrient intake and digestibility, nitrogen balance, and rumen fermentation kinetics in dairy goats. 2022.

94. Ventorino, V., A. Aliberti, V. Faraco, A. Robertiello, S. Giacobbe, D. Ercolini, A. Amore, M. Fagnano, O. Pepe, Exploring the microbiota dynamics related to vegetable biomasses degradation and study of lignocellulose-degrading bacteria for industrial biotechnological application, Scientific Reports, 5, 2015, 8161.

95. Vervaeke P., Navez F., Martin J., Tack F.M.G., Verloo M.G., Lust N., Behaviour of heavy metals during the gasification of willow wood harvested from contaminated sites. COST 837 WG2+4 Meeting in Stockholm, Sweden: Work-shop "Phytoremediation of toxic metals", June 12-15, 2003.

96. Wang, C., Kong, Y., Hu, R., Zhou, G., Miscanthus: A fast- growing crop for environmental remediation and biofuel production. *GCB Bioenergy*, *13*(1), 2021, 58-69.

97. Wang, Y., Wang, H., Li, R., Fan, X., Peng, Z., Wu, J., Duan, L. Biomass yield and quality of the *Miscanthus*× *giganteus* in northern China. *Agronomy Journal*, *114*(2), 2022, 1091-1099.

98. Weger J, Knápek J, Bubeník J, Vávrová K, Strašil Z. Can *Miscanthus* Fulfill Its Expectations as an Energy Biomass Source in the Current Conditions of the Czech Republic?—Potentials and Barriers. *Agriculture*. 11(1):40. 2021.

99. Williams, C., T. Biswas, A. Downie, P. Rogers, Yield, salt tolerance and energy from *Arundo donax*: a potential biochar and biofuel crop, 1st Asia Pacific Biochar Conference Gold Coast, 2009, 48.

100. Wilts, H. D., Burton, D. L., Farooque, A. A., Schroeder, W. R., Murray, B., Murphy, E. K., & Ramsay, M. Economic potential of agricultural-riparian shrub willow: An evaluation of the biomass producing capabilities and costs of cultivating Salix viminalis downslope of potato cropping systems in PEI. *Biomass and Bioenergy*, *183*, 2024, 107-118.

101. Weih, M. Perennial energy crops: growth and management. Crop and Soil Sciences. In: Encyclopedia of Life Support Systems (EOLSS), developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, UK, 2009, 2-4.

102. Woźniak M, Gałązka A, Siebielec G, Frąc M. Can the Biological Activity of Abandoned Soils Be Changed by the Growth of *Paulownia elongata* × *Paulownia fortunei*?—Preliminary Study on a Young Tree Plantation. *Agriculture*. 12(2):128, 2022.

103. Woods, V. B. Paulownia as a novel biomass crop for Northern Ireland? Agri-Food and Bioscience Institute. *Occasional publication*, (7), 2008, 47.

104. Xue, W., Jiang, Y., Shang, X., & Zou, J. Characterisation of early responses in lead accumulation and localization of Salix babylonica L. roots. *BMC Plant Biology*, *20*, 2020, 1-15.

105. Xue, S.; Lewandowski, I.; Wang, X.; Yi, Z. Assessment of the production potentials of Miscanthus on marginal land in China. Renew. Sustain. Energy Rev. 54, 2016, 932–943.

106. Yang, J., Zhao, H., Zhang, T. Heat and drought tolerance of two willow species, Salix gordejevii and Salix babylonica: A comparative study. *Israel Journal of Plant Sciences*, *52*(4), 2004, 301-306.

107. Zaret, S. L. . *Volunteer Establishment of Miscanthus× giganteus Vegetative Propagules: Implications for Biofuel Production* (Master's thesis, The Ohio State University), 2013.

108. Zachar, M., Lieskovský, M., Majlingová, A., Mitterová, I. Comparison of thermal properties of the fast-growing tree species and energy crop species to be used as a renewable and energy-efficient resource. *Journal of thermal analysis and calorimetry*, *134*, 2018, 543-548.

109. Zhaohua, E., A new farming system. crop/paulownia intercropping. multipurpose tree species from small-farm use. Proceedings of an international workshop held in November 2-5, Pattaya, Thailand, 1987, 65-69.

110. Zhang, Q., Jin, P., Li, Y., Zhang, Z., Zhang, H., Ru, G., Jiang, D., Jing, Y., Zhang, X. Analysis of the characteristics of paulownia lignocellulose and hydrogen production potential via photo fermentation. *Bioresource Technology*, *344*, 2022,126361.

111. Zhuang, D.; Jiang, D.; Liu, L.; Huang, Y. Assessment of bioenergy potential on marginal land in China. Renew. Sustain. Energy Rev. 15, 2011, 1050–1056.

112. Faber, A., Pudełko, R., Borek, R., Borzecka-Walker, M., Syp, A., Krasuska, E., Mathiou, P. Economic potential of perennial energy crops in Poland. *J. Food Agric. Environ*, *10*(3-4), 2012, 1178-1182.

Mila Kaleva

Department of Infectious Microbiology
The Stephan Angeloff Institute of Microbiology,
Bulgarian Academy of Sciences
1113 Sofia, Bulgaria
e-mail: mdkaleva@microbio.bas.bg