

Improving energy efficiency of apple production by reduced application of pesticides

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Abstract: A large number of apple orchards are treated over 20 times during the vegetation period with high application rates (over 1000 L/hm²) or medium application rates (500-1000 L/hm²) of pesticides which require significant energy input. Experimental research was carried out in the Serbian region of Vojvodina with the aim to show the possibilities to reduce energy usage in apple production by reducing pesticide application rates (200-500 L/hm²) and smaller controlled number of treatments with pesticides while maintaining the biological efficiency of apple chemical protection. Research results showed that the cumulative life cycle energy demand of apple production in Vojvodina, assuming a typical 22 annual treatments and relatively high pesticide application rate (1150 L/hm²), was 48 GJ/hm² and energy output was 94 GJ/hm². Reduced number of treatments and lower pesticide application rates have a favorable impact on energy inputs associated with diesel fuel, machinery, chemicals, water and electricity consumption and usage, whereas other energy inputs remain unchanged. The energy input for 12 treatments with pesticide application rates of 381 L/hm² was 36 GJ/hm², which is a 25% reduction in comparison to 22 treatments with a pesticide application rate of 1150 L/hm². Reduced number of treatments and pesticide application rate increased the energy use efficiency from 1.96 to 2.61, energy productivity from 0.82 kg/MJ to 1.09 kg/MJ, and net energy from 46 GJ/hm² to 58 GJ/hm². Results also suggest that applying the correct IPM approach can easily lead to a strong reduction in the number of treatments and a major energy saving.

Keywords: apple production, energy flow, pesticide application rates, total energy input, energy balancing

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1 Introduction

Apple (*Malus silvestris*) is one of the main fruit crops in Europe and it is the 4th ranked fruit in the world after banana, citrus, and melons. Apple fruit is very important from the economic aspect as well because it belongs to the category of fruits which require highly complex production technology, considerable labor input and financial resources, but it is highly accumulative and cost effective. In comparison to wheat production, apple growing provides 10-20 times as much production value per hectare^[1].

Apple is the second most commonly grown fruit in Serbia (15% out of all fruit crops), preceded by the plum. Apple is the most frequently grown fruit in Vojvodina, which is in the northern

part of the Republic of Serbia and the most important agricultural region. More than one third (ca. 77 000 t) of the total annual production of apples in Serbia (ca. 200 000 t) is grown in Vojvodina^[1]. According to statistical data from 2007, the biggest number of fruitful trees could be found in the South-Banat region of Vojvodina (1.2 million) and North-Bačka region (1 million) where 20 kg of fruit per tree was an average yield. After 2007, the size of the apple orchards increased both in Vojvodina and Serbia.

The total land used for apple orchards in Serbia is 23 737 hm², out of which 6347 hm² is located in Vojvodina^[2]. Apple production technology with inter-row distance from 3.6 m to 4 m and 1.2 m to 1.6 m of the distance between trees in the rows is applied on over 80% of the planting area. These orchards do not have installed anti-hail nets and they are usually not irrigated. Only 13.4% of land which is used for fruit production is irrigated^[2]. Those are mainly soft fruits and modern high density apple orchards which have become more and more common over the last 5 to 10 years. Nowadays, there are less than 20% of high density apple orchards (3.2 m×0.6-0.8 m) which have an irrigation system and anti-hail nets.

One problem particularly related to apple growing is the number of chemical treatments and application rates. One of the previous research showed that more than 60% of orchards were treated more than 20 times (22 treatments on average) with high (over 1000 L/hm²) or medium (500-1000 L/hm²) pesticide application rates^[3]. This number of more than 22 treatments per year is useless and very dangerous from an environmental and

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healthy point of view.

Energy flow was also tested in the integral apple production in Greece^[4]. Chemical protection made 40% of total energy input. The results of their research showed that energy saving can be achieved by reducing the fertilization (especially N) and application of chemical agents, as well as by implementing adequate technology without significant reduction in yield quality and quantity. The energy input for chemical protection depends primarily on the climate where apples are grown. The energy input for chemical protection in Turkey is 18.1%^[5], and in Iran, it is only 12.3% of total energy input^[6].

High pesticide application rates and a number of treatments imply high energy input, increased production costs and a threat from the aspect of environmental protection. During the application of chemical agents, the losses of fluid that occur due to air and ground drift pose danger because of soil and air pollution. The reduction of potential risks of polluting natural resources is ensured with a reduced number of treatments and lower pesticide application rates.

The objective of this research was to determine the main energy inputs for the production technology applied in the Vojvodina region, the Republic of Serbia. This research also aimed at indicating the possibilities of reduced energy inputs with respect to chemical protection by using lower pesticide application rates (200-500 L/hm²) and smaller controlled number of treatments but maintaining the biological efficiency of apple chemical protection. The analysis of apple production technology was conducted in 2009 and 2010 with particular attention paid to chemical protection.

2 Materials and methods

2.1 Orchard characteristics

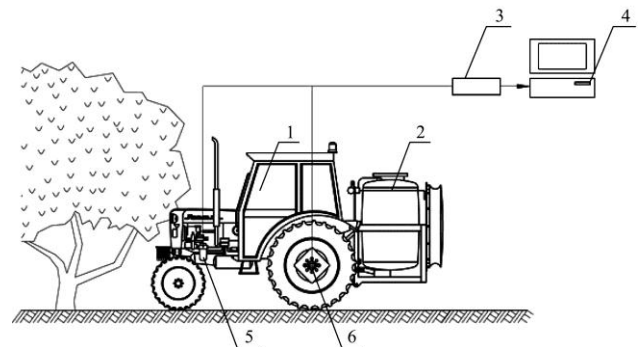
The research was conducted at an orchard managed by the Department of fruit growing, viticulture, horticulture and landscape architecture (45°20'18.9"N; 19°50'30"E) of the Faculty of Agriculture in Novi Sad, Serbia. The Idared apple orchard was established in 1997 on M9 rootstock, with a slender spindle type of training system. It was established on degraded chernozem soil with 3% organic matter content. Macro relief is flat, and microrelief is mostly flat with slight depression between the rows, about 10 cm deep. The planting distance is 4×1.2 m and the orchard is not equipped with anti-hail nets or irrigation systems. Given these characteristics, it could be considered as a typical apple orchard in Vojvodina, Serbia.

2.2 Inputs associated with apple production

During the research, all relevant inputs of material, energy and human labor were systematically monitored and measured. The productivity (hm²/h) and fuel consumption (L/hm²) of specific agrotechnical operations were determined based on on-site measurements. Fuel consumption was measured by the volume method using the *Pierburg 2911* flow meter (accuracy level ±0.5%), Figure 1.

The working speed was measured with a device installed on the tractor rear wheel. The instrument was built-in *Optocapler*

GPIA70R (Sharp) sensors (produced by TRCpro, Serbia). Eight-channel acquisition unit *Spider8* (HBM, Germany) connected to PC was used for the data collection and storage^[7].



1. Tested tractor 2. Air assisted sprayer 3. Acquisition (Spider 8) 4. PC 5. Fuel flow meter Pierburg 2911 6. Velocity sensor (Optocapler GPIA70R Sharp)

Figure 1 Scheme of measuring equipment

2.3 Insect/disease control

The apple orchard was treated 12 times out of which two treatments included only fungicides, whereas ten treatments were a combination of fungicides and insecticides, Table S1. In contrast to the more than 20 treatments with application high pesticide application rate over 1000 L/hm², typically applied preventively in Vojvodina when constant monitoring of disease and pest development is not possible^[8]. The orchard was divided into three parts: the control part, and parts treated with medium and low pesticide application rates which were 759 L/hm² and 381 L/hm², respectively. Biological efficiency of reduced pesticide application rate and the number of treatments was studied during the two years of the experiment.

Applications of insecticides and fungicides were performed with a carried air assisted sprayer *Agromehanika 440 (AGP 440)* mounted on a tractor *Rakovica 65* with a nominal power of 47 kW. The sprayer had a 400 L tank. The fan was axial with adjustment of fan speed (12 to 32 m/s), max 1400 r/min fan rotating speed and airflow capacity (16 000 to 48 000 m³/h). The air assisted sprayer was equipped with 12 *Lechler TR 80-02* nozzles for low rates and 12 *Lechler TR 80-04* nozzles for medium and high pesticide application rates which were under pressure of 8 bar for low and medium rates, and 15 bar for high pesticide application rate. Duration and fuel consumption of specific operations associated with chemical protection of apple orchard by air assisted sprayer is given in Table 1. The longest amount of time was spent on the forming spraying aggregate and traveling from the commercial yard to the orchard, and its return (4000 s). The orchard had a water source so the tank was filled and work fluid was prepared there. The average distance from the point of tank filling to the point of treatment in the orchard was about 1 km. The average working speed of the aggregate during treatment was 5.70 km/h. The length of rows in the tested orchard is 200 m long. Treatment of one row lasted for 127 s with fuel consumption of 4.20 L/h. The turning of the aggregate at the end of the rows required, on average, additional 30 s (Table 1).

Table 1 Measured value of working time structure and fuel consumption during the treatment of apple orchard (2009 and 2010)

Working time structure	Time parts ($x_{i,j}$)/s	Working speed/km h ⁻¹	Hourly fuel consumption/L h ⁻¹	Fuel consumption ($x_{i,f}$)/L
Preparation and finishing activities (x_1)	4000	–	3.04	3.378
Preparation of fluid for the treatment (x_2)	600	–	2.73	0.456
Travelling to the orchard (x_3)	630	5.81	3.19	0.559
Treatment (one row) (x_4)	127	5.70	4.20	0.148
Turning at the end of the row (x_5)	30	0.35	2.73	0.023
Driving back (x_6)	600	5.79	3.04	0.532

Based on the measured values presented in Table 1 several parameters such as labor productivity and annual fuel consumption can be derived which serve as the basis for energy balance. Treatment of one row covers an area of 800 m², therefore, at pesticide application rates of 381 L/hm², 759 L/hm² and 1150 L/hm² the consumption per one row is 30.48 L, 60.72 L and

90.00 L, respectively (Table 2). The time required to empty one tank (*c*) was determined based on the number of rows treated with one tank (*b*, Table 2) and the estimated working time ($x_{i,t}$) associated with each of the operation (Table 1) using the following equation:

$$\text{Time required to empty one tank (c)} = x_{2,t} + x_{3,t} + x_{6,t} + (x_{4,t} + x_{5,t}) b \quad (1)$$

Table 2 Calculated values of productivity, working hours and fuel consumption for pesticide application rates and number of treatments

Symbol	Parameter	Unit	Pesticide application rates/L hm ⁻²		
			381	759	1150
<i>a</i>	Application rate per one row	L row ⁻¹	30.48	60.72	90.00
<i>b</i>	Number of rows treated with one tank	–	12	6	4
<i>c</i>	Discharging period of one tank, eq. 1, <i>c</i>	s	3744	2802	2488
<i>d</i>	Area treated with one tank, $d=0.08 \text{ hm}^2 \times b$	hm ²	0.96	0.48	0.32
<i>e</i>	Number of cycles (tank discharges) for 8 hours, $e=(8 \text{ h} \times 3600 \text{ s} - x_{1,t})/c$	–	6	8	9
<i>f</i>	Productivity for 8 h, $f=e \times d$	hm ² ·8h ⁻¹	5.76	3.84	2.88
<i>g</i>	Productivity, $g=f/8$	hm ² h ⁻¹	0.72	0.48	0.36
<i>h</i>	Working hours per one treatment, $h=1/g$	h hm ⁻²	1.39	2.08	2.78
<i>i</i>	Total working hours (12 treatments), $i=h \times 12$	h hm ⁻²	16.67	25.00	33.33
<i>j</i>	Total working hours (22 treatments), $j=h \times 22$	h hm ⁻²	30.56	45.83	61.11
<i>k</i>	Fuel consumption for one tank of a sprayer, eq. 2, <i>k</i>	L tank ⁻¹	3.597	2.572	2.230
<i>l</i>	Fuel consumption per unit of treated area, $l=((e \times k) + x_{1,t})/f$	L hm ⁻²	4.333	6.238	8.143
<i>m</i>	Total annual fuel consumption (12 treatments), $m=1 \times 12$	L hm ⁻²	52.00	74.86	97.71
<i>n</i>	Total annual fuel consumption (22 treatments), $n=1 \times 22$	L hm ⁻²	95.33	137.24	179.14

Labor productivity per hour was calculated as a ratio between the treated area and time required for the treatment, and with respect to the pesticide application rate, it was 0.72 hm²/h, 0.48 hm²/h and 0.36 hm²/h (Table 2). The total working hours required for different numbers of treatments and pesticide application rates were determined (Table 2) based on the productivity and served as input value in energy balancing. It was assumed that the application of insecticides and fungicides requires only one worker (tractor operator).

The amount of fuel consumed during the period while one sprayer tank is fully discharged (*k*) was calculated with Equation (2) using the values of fuel consumption ($x_{i,t}$) for individual operations during treatment (Table 1) and the number of rows treated with one tank (*b*) with respect to the pesticide application rate (Table 2). Based on this value the fuel consumption per unit of area and the annual fuel consumption for 12 and 22 treatments could be also determined (Table 2).

$$\text{Fuel consumption for one tank of a sprayer (k)} = x_{2,t} + x_{3,t} + x_{6,t} + (x_{4,t} + x_{5,t}) b \quad (2)$$

The annual fuel consumption required for the application of pesticides varied in a significant range from 52 to 179 L/hm² depending on the number of treatments and pesticide application rates (Table 2).

2.4 Other agrotechnical operations

Apart from insect/disease control, the production technology involves tillage, weed control, harvesting, pruning, mulching and application of fertilizers. Tillage was performed four times during the year with a surface cultivator at a depth of 13 cm. Weed control was carried out three times a year with a manual sprayer that had a 10 litre tank. The treated parts were only those that were not tilled with a cultivator. The herbicide used was based on glyphosate active ingredient. Mineral fertilizers (NPK 8:16:24) were applied with a spreader that was pulled between rows and the application rate of fertilizer was 400 kg/hm². Manual pruning was performed with pruning shears and saws in autumn, and the

pruning wood was mulched with *INO Brežica* mulcher with 1.6 m working width. Surface cultivator with 2 m work width was used for soil tillage, incorporation of mineral fertilizer and pruning wood, and for weed removal.

Apples were harvested and selected manually three times and stored in wooden crates. The average yield at various application rates was 39 240 kg/hm² with a standard error of 2132 kg/hm². At 5% significance threshold, there were no statistically significant differences between yields. The observed minor variations in yields were not the consequence of differences in the application rate and the number of treatments^[3]. Therefore, to make the different production systems comparable, the average yield of 39240 kg/hm² was used throughout the energy balancing. The fruit was transported 1 km to the commercial yard in a tractor-trailer with a net load of 8 t.

2.5 Summary of inputs associated with apple production

Average values of input of labor, fuel and chemical agents that were used for technological operations during the two-year-long research are summarized in Table 3.

2.6 Energy equivalents of input and output flow

The total energy equivalent is calculated by multiplying the inputs with respective energy equivalents. The energy equivalent of input equals the quantity of primary energy used in the whole life cycle of input. Energy equivalents of various inputs are available from published sources and there are often used in energy balancing of agricultural products^[4,5,9]. However, there is an enormous variation in energy equivalents reported in the literature. The energy equivalent of a specific input may vary in significant range depending on the chosen spatial and temporal system boundaries, the production technologies and methods used for its estimation^[10]. Thus, instead of relying on pre-calculated values from previous studies, in this study, the input specific energy equivalents were calculated using the cumulative energy demand (CED) method^[23,24].

Table 3 Inputs per hectare for each operation

Field operation	Repetition	Labour/h hm ⁻²	Fuel/L hm ⁻²	Water/m ³ hm ⁻²	Electricity/kWh hm ⁻²	Chemicals/kg hm ⁻²
Cultivation	4	4.39	32.89	–	–	–
Weed control	3	24	–	–	–	3.6 **
Insect/disease control						4.1/18.2** (4.6/31.4)
381 L hm ⁻²	12	16.7 (30.6)	52.0 (95.3)	4.8 (8.8)	1.3 (2.4)	
759 L hm ⁻²	(22)*	25.0 (45.8)	74.9 (137.2)	9.6 (17.6)	2.6 (4.8)	
1150 L hm ⁻²		33.3 (61.1)	97.7 (179.1)	14.4 (26.4)	3.9 (7.2)	
Harvesting	3	392	–	–	–	–
Transport with trailer	1	24	4.2	–	–	–
Pruning	1	120	–	–	–	–
Mulching pruning	1	1.10	7.1	–	–	–
Fertilizer application	1	0.73	3.5	–	–	400

Note: * Values given in brackets refer to 22 treatments; ** Data refers to the mass of active ingredients, Table S1

Besides the direct energy input for production, use and disposal of a product, the CED method also determines the primary energy (both renewable and non-renewable) needed for the production of facilities, raw materials, auxiliary materials and consumables associated with the life cycle of the product investigated^[11]. The CED of various inputs was determined by process chain analysis according to the ISO 14040:2006 following the principles of the attributional LCA. The CED analysis is based on the results of life cycle inventory (LCI) analysis which includes information on the type and quantity of natural resources used in unit processes associated with the life cycle of a product. These data are available from the *Ecoinvent v. 2.2* LCI database^[25] which is considered to be the most comprehensive LCI database in Europe. This database is integrated into the *SimaPro 8* LCA software which was used for the calculations.

For fuels and material inputs that are already included in the *Ecoinvent* database (fertilizers, diesel fuel, lubricants, electricity, water for plant protection) the calculation of energy equivalent is straightforward. However, some inputs are not available in the database (pesticides, wooden boxes) or need certain adoption (agricultural machines and equipment) before used in the *SimaPro* software.

The *Ecoinvent* LCI database provides information on primary energy associated with the production, maintenance and disposal of 1 kg agricultural machinery. The amount of machinery (in kg/hm²) needed for a specific process in apple production was calculated using Equation (3)^[26]. Information on typical weight and life time of selected agricultural machinery are available from literature shown in Table 4^[26], whereas the operation time (h/hm²) of the machinery involved in apple production was calculated from data in Table 3.

$$\text{Amount of machinery (AM)} = \frac{\text{Weight} \cdot \text{Operation time}}{\text{Life time}} \quad (3)$$

Data on primary energy consumption in the life cycle of some pesticides used in apple production are not available in the *Ecoinvent* LCI database; therefore, they were estimated using literature data. Table S2 summarizes the results of the literature review regarding the CED of different types of pesticides. Although there are several research papers published in the subject (Table S2) almost all of the references to the CED of pesticides can be traced back to the original data of [27]. Only a few active ingredients of pesticides used in Serbian apple production are covered with previous research. For those active ingredients which are not listed in [27] or other relevant sources the respective CED values were approximated using one of the following

procedures: a) if the CED value for the specific active ingredient is missing, but it is available for the substance group the active ingredient belongs, then the average energy requirement of the substance group was attributed to the missing active ingredient; b) if data on CED of the active ingredient or its respective substance group are both missing, then the average energy requirement of the pesticide type (e.g. herbicides or insecticides) was assigned to the missing active ingredient. The single energy equivalent figure (488 MJ/kg active ingredient (a.i.) for herbicides; 161.5 MJ/kg a.i. for fungicides; 273.5 MJ/kg a.i. for insecticides), which describes the average CED of different types of pesticides, is calculated as the weighted average of pesticides used in apple production in Serbia.

Table 4 Typical weight and life time of agricultural machinery^[26] and their respective operation time

Machine	Weight /kg	Life time /h	Operation time/h*		AM/kg hm ⁻²	
			12 treat.	22 treat.	12 treat.	22 treat.
Tractor (47 kW)	3300	7200	46.9-63.6	60.8-91.3	21.5-29.1	27.9-41.9
Field cultivator	550	720	4.39	4.39	3.4	3.4
Fertilizer broadcaster	200	1500	0.73	0.73	0.1	0.1
Sprayer	200	700	16.7-33.3	30.6-61.1	4.8-9.5	8.7-17.5
Trailer (8 t)	1500	1200	24.00	24.00	30.0	30.0
Rotary harrow	900	540	1.10	1.10	1.8	1.8

Note: * Data on operation time are available from Table 3.

Life cycle inventory data of wooden boxes used for transportation of apples is not included in the *Ecoinvent* database. Therefore, the appropriate CED value was taken from a European study of different packaging systems^[28]. According to the study, the life cycle primary energy demand of a standard non-reusable wooden box (weight 0.9 kg; dimensions 600 mm×400 mm×240 mm; load weight 15 kg) is 29.1 MJ. The primary energy demand for wooden boxes is mainly based on solar energy captured via photosynthesis and only 5.7 MJ of CED comes from non-renewable sources. Many argue that solar energy should not be included in the energy balancing of agricultural systems since, unlike the fossil energy reserves solar energy is practically infinite in the total amount^[29]. If no stock is depleted, then no opportunity cost is incurred^[30]. Given these considerations, solar energy embodied in biomass is excluded from energy balancing in this paper. In the reference study^[28] it was assumed that after the use phase 100% of wooden boxes are incinerated and that the energy recovered is used to substitute the average electricity in EU which is generated mainly from non-renewable

energy sources. This explains the negative CED value of wooden boxes in Table 5. Assuming that there is no end of life

(EoL) energy recovery the non-renewable CED of the wooden box would be 6.3 MJ/kg^[28].

Table 5 Energy equivalents of various inputs used in apple production in Serbia

Inputs	Unit	Energy equivalent/MJ unit ⁻¹				
		Total	Non-renewable	Renewable	Direct	Indirect
Pesticides						
Herbicides	kg a.i.	488.0	476.3	11.7	0.0	488.0
Insecticides	kg a.i.	273.5	266.9	6.6	0.0	273.5
Fungicides	kg a.i.	161.6	157.7	3.9	0.0	161.6
Fertilizers						
Nitrogen	kg N	63.6	62.4	1.2	0.0	63.6
Phosphate (P ₂ O ₅)	kg P ₂ O ₅	24.6	23.6	1.0	0.0	24.6
Potassium (K ₂ O)	kg K ₂ O	9.6	9.4	0.3	0.0	9.6
Agricultural machines and equipment						
Tractor	kg	133.3	126.2	7.2	0.0	133.3
General	kg	75.3	71.2	4.1	0.0	75.3
Tillage	kg	85.1	80.3	4.8	0.0	85.1
Trailer	kg	85.1	77.0	8.1	0.0	85.1
Diesel fuel	L	46.4	46.3	0.1	38.9	7.5
Lubricant	L	46.4	46.3	0.1	0.0	46.4
Wooden boxes (with EoL energy recovery)	kg	-11.5	-6.0	-5.5	0.0	-11.5
Wooden boxes (no energy recovery)	kg	6.3	6.3	0	0.0	6.3
Water for plant protection	m ³	0.9	0.9	0.0	0.0	0.9
Electricity	kWh	12.1	10.9	1.2	3.6	8.5
Output						
Apple*	kg	2.4				

Note: * The energy output is calculated based on the calorific value of the harvested apple (2.4 MJ/kg^[41]).

Table 5 summarizes the energy equivalents of various material inputs used in apple production with references to the *Ecoinvent* process or literature used to estimate its value. Agricultural energy demand can be divided into direct and indirect energy needs^[10]. Direct energy is the energy consumed on the farm in the form of diesel fuel and electricity to power the engines. Indirect energy is the energy consumed beyond the farm for the provision of the production means (Table 5). Furthermore, total energy demand can be divided into non-renewable and renewable based on the form of primary energy source. For most of the inputs the share of non-renewables and renewables, their total energy equivalent was calculated using the CED method^[11] and the appropriate *Ecoinvent* LCI dataset. The literature used to estimate the CED of various pesticides did not make distinctions between the origins of energy consumed in the life cycle of pesticides; therefore, it was assumed that 97.6% of the energy demand is fulfilled from non-renewable energy sources. The former value corresponds with the average share of non-renewable energy sources in the life cycle energy requirements of all the pesticides included in the *Ecoinvent* v. 2.2 LCI database.

Human labor is not usually considered in the energy balance of the agricultural production system^[10] since this input is hard to convert to energy figures. Energy costs of human labor might include only the energy for the maintenance of the body, or the energy required to produce food consumed during working hours, or might consider the total energy sequestered in products and services which are used by the agricultural producer and its family^[12]. The default scenario (S0) does not consider human labor as input in the energy balance. However to demonstrate the extent to which the chosen approach may influence the results of energy analyses three different methods were used to quantify the energy equivalent of agricultural labor. In the first scenario (S1) 2.5 MJ was assumed as the energy equivalent of 1 h of human labor. A similar value is commonly used in the energy balancing of apple

production systems^[4,5,9] and refers to the nutritional requirements of workers^[13]. Scenario 2 takes into account not only the energy content of food consumed by the worker but also the energy required for its provision. As a representative value for this scenario, a 20 MJ/h was chosen which is within the range suggested by [14]. In this study, 82 MJ/h was assumed as the highest value (S3) estimated based on the average energy input per working member of society in Serbia using the method recommended by [13].

2.7 Estimation of energy efficiency parameters

Energy efficiency parameters are calculated in order to determine the dependencies between the amount of energy consumption and total energy output and production per hectare. Energy efficiency parameters were determined based on the commonly used equations^[5,9,15-20]. Energy use efficiency (energy input-output ratio), specific energy, energy productivity and net energy were calculated by using total energy inputs and outputs for a unit of surface area (MJ/hm²) and apple yield (kg/hm²) in the following equations:

$$\text{Energy use efficiency (energy ratio)} = \frac{\text{Energy output (MJ/hm}^2\text{)}}{\text{Energy input (MJ/hm}^2\text{)}} \quad (4)$$

$$\text{Energy productivity} = \frac{\text{Apple output (kg/hm}^2\text{)}}{\text{Energy input (MJ/hm}^2\text{)}} \quad (\text{kg/MJ}) \quad (5)$$

$$\text{Specific energy} = \frac{\text{Energy input (MJ/hm}^2\text{)}}{\text{Apple output (kg/hm}^2\text{)}} \quad (\text{MJ/kg}) \quad (6)$$

$$\text{Net energy} = \text{Energy output (MJ/hm}^2\text{)} - \text{Energy input (MJ/hm}^2\text{)} \quad (\text{MJ/hm}^2) \quad (7)$$

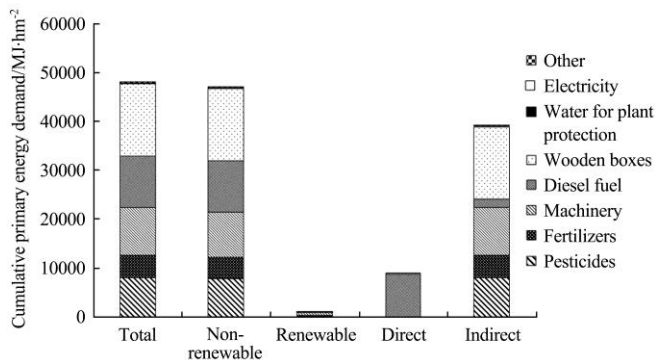
3 Results and discussion

Table 6 and Figure 2 show the type of inputs associated with apple production and their corresponding life cycle energy equivalents.

Table 6 Cumulative energy demand for apple production (for 22 treatments and application rate of 1150 L/hm²)

Flows	Unit	Quantity per unit area/hm ²	Total energy Equivalent/MJ hm ⁻²	Total non-renewable energy equivalent/MJ _{nr} hm ⁻²	Share in total energy/%
Human labour	h	627.7	0	0	0.0 (0.0)
Pesticides		0.0	8097	7903	16.8 (-100.6)
Herbicides	kg a.i.	3.6	1757	1715	3.7 (28.4)
Insecticides	kg a.i.	4.6	1269	1239	2.6 (20.5)
Fungicides	kg a.i.	31.4	5071	4949	10.5 (81.9)
Fertilizers		0.0	4535	4410	9.4 (73.3)
Nitrogen (as N)	kg	32.0	2036	1997	4.2 (32.9)
Phosphate (as P ₂ O ₅)	kg	64.0	1574	1513	3.3 (25.4)
Potassium (as K ₂ O)	kg	96.0	925	900	1.9 (14.9)
Machinery		0.0	9897	9258	20.6 (159.9)
Tractor	kg	41.9	5581	5282	11.6 (90.2)
Field cultivator	kg	3.4	285	269	0.6 (4.6)
Fertilizer broadcaster	kg	0.1	7	7	0.0 (0.1)
Sprayer	kg	17.5	1314	1243	2.7 (21.2)
Trailer	kg	30.0	2553	2311	5.3 (41.2)
Rotary harrow	kg	1.8	156	147	0.3 (2.5)
Diesel fuel	L	226.8	10521	10497	21.9 (170.0)
Lubricant	L	2.3	105	105	0.2 (1.7)
Wooden boxes	kg	2354.4	-27076 (14833)	-14126 (14833)	30.8 (-437.4)
Water for plant protection	m ³	26.4	24	24	0.0 (0.4)
Electricity	kWh	7.2	87	78	0.2 (1.4)
Total inputs			6190 (48099)	18149 (47108)	100 (100)
Apple	kg	39240	94176	94176	100
Pruning wood	kg	3080	0	0	0.0
Total outputs			94176	94176	100

Note: * Data in brackets refer to the scenario when no energy recovery is assumed after the use phase of the wooden boxes, e.g. wooden boxes are landfilled.



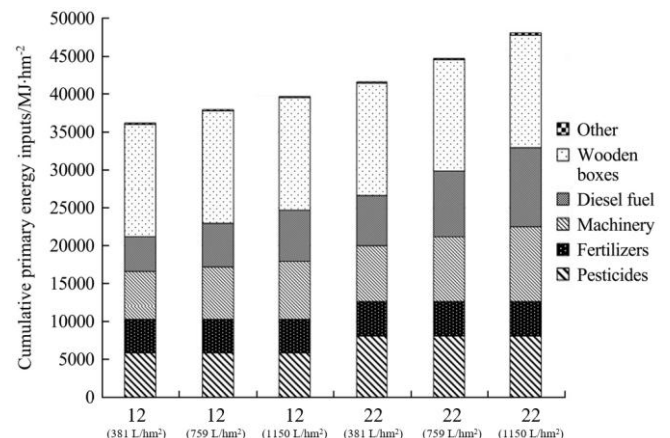
Note: Assuming no energy recovery at EoL of wooden boxes.

Figure 2 Primary energy demand for apple production differentiated according to energy type (for 22 treatments and application rate of 1150 L/hm²)

Detailed results are provided only for the scenario which involves 22 annual treatments with an application rate of 1150 L/hm² which is usually the case with chemical protection of apple fruit that is applied in Vojvodina and other regions in central Europe with similar climatic conditions^[8]. Aggregated results of other scenarios assuming different numbers of treatments and application rates are provided in Figures 3 and 4.

Assuming no energy recovery at the EoL of wooden boxes and 22 treatments per year with an application rate of 1150 L/hm² the primary energy demand of apple production was estimated at 48 GJ/hm² which is significantly less than the calorific value of the apple output (94 GJ/hm²; Table 6). Almost one-third of the total primary energy inputs are associated with the use of wooden boxes. Disposable wooden boxes weighed 2354 kg/hm², and their production required 15 GJ/hm². Energy inputs associated with agricultural mechanization have a significant share (~30%) in total CED due to significant energy required for the provision of diesel

fuel and the production and maintenance of agricultural machinery. Research results indicate that pesticides and fertilizers are also important contributors to the CED of apple production making around 17% and 9% of the total CED, respectively.



Note: Assuming no energy recovery at EoL of wooden boxes.

Figure 3 Changes of individual energy inputs with respect to the application rate and number of treatments

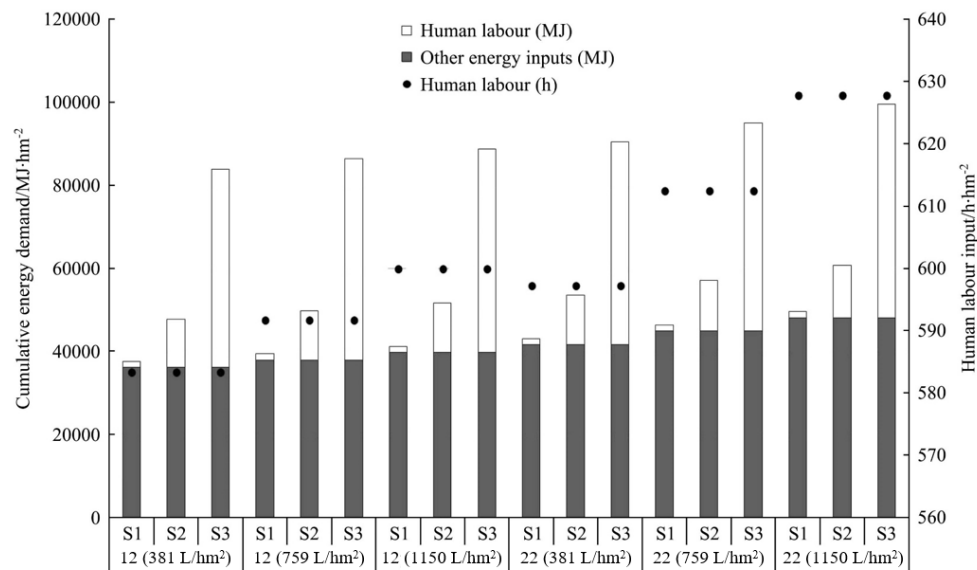
Figure 3 shows the variation of CED (without considering human labor and solar energy captured via photosynthesis as energy inputs) with respect to different application rates (381, 759 and 1150 L/hm²) and the number of treatments (12 and 22). The total CED value ranged from 36.1 GJ/hm² to 48.1 GJ/hm² depending on the norms and the number of treatments. Reduced number of treatments and application rates reduced energy inputs associated with diesel fuel, machinery, chemicals, water and electricity, while the rest of the energy inputs remained unchanged (Figure 3). By reducing the number of treatments from 22 to 12, and application rate from 1150 L/hm² to 381 L/hm², the use of

machinery reduced from 91.3 h/hm² to 46.9 h/hm², which provides a saving of 3.7 GJ/hm². Simultaneously, 127.14 L/hm² of diesel fuel (or 5.9 GJ/hm²) was saved. A smaller number of treatments reduced the quantities of used insecticides and fungicides by 2.6 kg/hm² and 27.7 kg/hm², respectively, which resulted in a saving of 2.6 GJ/hm².

Figure 4 shows the human labor requirement of apple production (h/hm² and MJ/hm²) and the contribution of human labor to the total energy demand assuming different energy equivalent of a unit of human labor. Considerable saving in human labor hours (ca. 44 h/hm²) can be achieved by reducing the number of treatments from 22 to 12, and application rate from 1150 L/hm² to 381 L/hm². Depending on the applied method for

the determination of the energy equivalent of human labor, as well as the norms and number of treatments, the total energy input ranged from 37.57 GJ/hm² to 94.46 GJ/hm².

Table 7 shows that the reduced number of treatment and application rates considerably improves the energy efficiency of apple production. Also, reduced the number of treatment decrease dangerous from an environmental and healthy point of view. By reducing the number of treatments and application rates the energy use efficiency, energy productivity, specific energy and net energy could be reduced by 24.9%, 24.8%, -33.7% and 20.6%, respectively. It should be noted that the energy balance did not include human labor and solar energy captured in biomass.



Note: Assuming no energy recovery at EoL of wooden boxes.

Figure 4 Inputs of human labor with respect to the application rate and number of treatments with pesticides

Table 7 Calculated energy efficiency parameters of apple production

	Number of treatments					
	12			22		
Application rate/L hm ⁻²	381	759	1150	381	759	1150
Energy use efficiency	2.61	2.49	2.37	2.27	2.10	1.96
Energy productivity/kg MJ ⁻¹	1.09	1.04	0.99	0.94	0.88	0.82
Specific energy/MJ kg ⁻¹	0.92	0.97	1.01	1.06	1.14	1.23
Net energy/GJ	58.06	56.28	54.50	52.60	49.34	46.08

Note: * Assuming no energy recovery at EoL of wooden boxes.

The obtained energy efficiency parameters in this study are relatively favorable if compared to the results of similar studies in other countries. In the reviewed studies^[4-6,9,6,21,22], the specific energy of apple production ranged between 1.59 MJ/kg (Turkey) and 2.8 MJ/kg (Germany). Differences in region-specific energy requirements and yields can largely explain the variations in the obtained energy efficiency parameters; however, it is important to note that the results of various studies are not always comparable due to different system boundaries and methodological approaches applied. These differences are mainly observable in the methods used to calculate the output side of the energy balance and the approaches used to account for the energy associated with human labor input and wooden boxes.

In this study, on the output side, only the energy content of the harvested apple was considered. The energy content of pruning

wood was not accounted for on the output side since pruning wood is usually chopped and spread over the orchard in Vojvodina. In some similar studies, researchers assign energy value for pruning wood^[4,5] which can significantly improve the energy ratio of apple production. This approach is acceptable only in cases when pruning wood is used for energetic purposes. In that case, however, the nutrients removed with pruning wood should be balanced with additional amounts of manure and/or mineral fertilizers which increase the input side of the energy balance. Based on [4] it can be estimated that the removal of 1000 kg of pruning wood would lead to the removal of 5.53 kg N, 1.24 kg P₂O₅ and 2.75 kg P₂O₅ from the soil. Consequently, each ton of pruning wood removed would increase the input side of energy balance by 408 MJ due to the additional use of fertilizers.

Research results indicate that the choice of whether to include human labor on the input side of the energy balance can significantly affect the results. In several previous studies, the energy cost of human labor was included in the energy balancing of apple production^[4,5,9]. However, it is important to note that the inclusion of human labor is rather controversial. Fossil energy and human labor are too different to be expressed in the same unit; consequently, there are hardly comparable^[29]. Furthermore, there are at least nine different methods to estimate the energy equivalent of human labor^[12] with estimates ranging from 0.2 MJ/h to 20 GJ/h^[14]. As indicated in Figure 4, the results of energy balancing are very sensitive to the chosen method used to determine the energy equivalent of human labor. The share of

human labor in total energy inputs of apple production can be less than 4%, if calculated based on the physical needs of humans, or higher than 50%, if the social energy consumption is considered as the basis for its determination.

Another important source of confusion is the assumed end-of-life scenario for wooden boxes. The estimated energy demands of apple production vary in a significant range depending on the assumed end of life scenario for wooden boxes (e.g. landfilling vs. incineration with energy recovery). Since the solar energy bounded in biomass via photosynthesis was not considered as energy input in the study, and due to the negligible consumption of other renewable energy sources in the life cycle of inputs (Table 5), the primary non-renewable energy demand is similar to total primary energy demand. If energy recovery from wooden boxes is an option; for example, the used wooden boxes incinerated in municipal solid waste incineration plant with energy recovery, then the total CED of apple production can be significantly reduced (from 48 to 6.2 GJ/hm² assuming that 100% of wooden boxes are incinerated; Table 6).

4 Conclusions

Regardless of the high uncertainties the presented analysis clearly shows that a smaller number of treatments and reduced application rates reduce energy consumption in apple production. Furthermore, it minimizes the risk of contamination of soil and the environment. Bad pesticide application causes over 25% and even 35% of pesticide to fall on the ground. Losses due to ground drift analyzed in Idared apple orchard which was 7 years old and concluded that losses were 325.3 L/hm² with 1289 L/hm² application rate and operating pressure of 15 bar^[3]. Reduced application rate to 801 L/hm² and operating pressure of 8 bar caused ground drift to decrease to 50.3 L/hm². Normally, the given results are not a general rule but a result of good calibration and careful consideration of weather conditions in which the treatment was carried out. Together with the timely identification of pathogens and a good choice of agents, all three factors influencing the efficiency and acceptability of chemical agents from ecological aspects are met. This also provides conditions for a smaller number of treatments with low application rates, as well as some energy saving. It should be particularly noted that the efficiency of low rates and a small number of treatments depends on the adjustment of nozzles and all work parameters (traveling speed, air velocity, operating pressure, selection of nozzles) to weather conditions in the orchard.

The results of this research would not be sufficient if the biological efficiency of low and medium application rates, as well as the reduced number of treatments, was not proved. This is why the analysis of the biological efficiency of low and medium application rates was performed during 2009 and 2010. A two-year bio-efficiency trial on *Venturia inaequalis* and *Podosphaera leucitricha* in apple confirmed that during suitable weather conditions, and with properly adjusted sprayer settings, a reduced application rate of 381 L/hm² gave the same quality of crop protection as a medium application rate of 759 L/hm^{2[3,32]}. Similar findings were reported by [1,31] who argue that under typical conditions in Vojvodina 12 treatments are sufficient if weather conditions and pest and disease development are constantly and carefully monitored. In order to accomplish that, the education of agricultural producers is necessary to allay the fear and eliminate prejudice about a smaller number of treatments which may cause inadequate chemical protection. Correct

application of pesticides with properly adjusted nozzles to the requirements of the orchard can ensure efficient protection with minimal losses caused by air drift.

Acknowledgements

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Appendix

Table S1 Type, active ingredient (a.i.) and application rate of pesticides used in apple production

No.	Fungicides		Insecticides		Total amount of pesticides /kg hm ²	Total amount of a.i. /kg hm ²
	Type	Rate/kg hm ²	Type	Rate/kg hm ²		
1.	Karathane-EC (dinocap 350 g/kg) Bakrocid S-25 (copper oxychloride 350 g/kg)	0.52+1.00	–	–	1.52	0.53
2.	Captan 50-W (captan 500 g/kg) Score 25-EC (difenoconazole 250 g/kg)	2.50+0.27	Prestige 290 FS (imidacloprid 40 g/kg and pencycuron 150 g/kg)	0.52	3.29	1.42
3.	Captan 50-WP Score 25-EC	2.50+0.27	Gusathion WP-25 (azinphos-methyl 250 g/kg)	2.00	4.77	1.82
4.	Captan 50-WP Rubigan-EC (fenarimol 120 g/kg)	2.50+0.55	Nurelle-D (chlorpyrifos 500 g/kg and cypermethrin 50 g/kg)	1.50	4.55	2.14
5.	Rubigan-EC Antracol WP-70 (propineb 700 g/kg)	0.55+2.00	Perfekthion-EC (dimethoate 400 g/kg)	1.80	4.35	2.19
6.	Alert-S (carbendazim 250 g/kg and flusilazole 125 g/kg) Antracol WP-70	0.554+2.5	Nurelle-D	1.50	4.55	2.78
7.	Captan 50-WP Score 250-EC Antracol WP-70	2.50+0.27	Calypto 480-SC (thiacloprid 480 g/kg)	0.29	3.06	1.46
8.	Sabithane (dinocap 225 g/kg and myclobutanil 75 g/kg) Kumuluf DF (sulphur 800 g/kg)	2.00+0.48+3.75	Fastac 10-EC (alfa-cypermethrin 100 g/kg)	0.19	6.42	4.56
9.	Captan 50-WP Rubigan-EC	2.50+0.55	Prestige 290 FS	0.52	3.57	1.34
10.	Delan 700-WG (dithianon 75 g/kg) Topas 100- EC (penconazole 100 g/kg)	0.31+0.25	Dimetoat EC (dimethoate 400 g/kg)	1.36	1.92	0.59
11.	Kossan-WG (sulphur 800 g/kg)	3.75	Mospilan 20-SP (acetamiprid 200 g/kg)	2.25	6.00	3.45
12.	Score 25-EC	0.27	–	–	0.27	0.068
	Total	32.33		11.94	44.27	22.34

Note: * Data in the table refer to the situation with 12 annual treatments. The scenario with 22 treatments includes five addition treatments with the combination of Captan 50-W, Score 25-EC and Prestige 290 FS pesticides (i.e. as the No 2 treatment) and five addition treatments with the combination of Captan 50-W and Score 25-EC pesticides (i.e. as the No. 2 treatment but without the insecticide).

Table S2 Primary energy used for production, formulation and packaging of pesticides according to various authors (MJ/kg a.i.)

Active ingredient	Pesticide type	Substance group	[27]****	[33]	[34]	[35]	[36]	In this study
Dinocap	Fungicide, Acaricide	Dinitrophenol	193*	n.a.	n.a.	210*	168*	190
Copper oxychloride	Fungicide, Repellent	Inorganic compound	n.a.	n.a.	n.a.	210*	168*	189
Captan	Fungicide, Bactericide	Phthalimide	135	n.a.	n.a.	210*	168*	135
Difenoconazole	Fungicide	Triazole	193*	n.a.	n.a.	210*	168*	190
Fenarimol	Fungicide	Pyrimidine	193*	n.a.	n.a.	210*	168*	190
Propineb	Fungicide	Carbamate	193*	n.a.	n.a.	210*	168*	190
Carbendazim	Fungicide, Metabolite	Benzimidazole	417**	400	410	210*	168*	405
Flusilazole	Fungicide	Triazole	193*	176	529	210*	168*	190
Myclobutanil	Fungicide	Triazole	193*	n.a.	n.a.	210*	168*	190
Sulphur	Fungicide	Inorganic compound	n.a.	n.a.	n.a.	210*	168*	189
Dithianon	Fungicide	Quinone	193*	n.a.	n.a.	210*	168*	190
Penconazole	Fungicide	Triazole	193*	n.a.	n.a.	210*	168*	190
Pencycuron	Fungicide	Phenylurea	193*	n.a.	n.a.	210*	168*	190
Fungicides (weighted average) ***								161.6
Imidacloprid	Insecticide, Veterinary substance	Neonicotinoid	234*	n.a.	n.a.	310*	214*	252
Azinphos-methyl	Insecticide, Acaricide	Organophosphate	234*	n.a.	n.a.	310*	214*	252
Chlorpyrifos	Insecticide	Organophosphate	181**	n.a.	324	310*	214*	324
Cypermethrin	Insecticide, Veterinary substance	Pyrethroid	600	583	600	310*	214*	594
Dimethoate	Insecticide, Acaricide, Metabolite	Organophosphate	181**	n.a.	n.a.	310*	214*	228
Thiacloprid	Insecticide, Molluscicide	Neonicotinoid	234*	n.a.	n.a.	310*	214*	252
Alpha-cypermethrin	Insecticide, Veterinary substance	Pyrethroid	234*	n.a.	518	310*	214*	252
Acetamiprid	Insecticide	Neonicotinoid	234*	n.a.	n.a.	310*	214*	252
Insecticides (weighted average) ***								273.5
Glyphosate, isopropylamine salt	Herbicide	Phosphonoglycine	474	n.a.	474	550	454	488
Herbicides (weighted average) ***								488

Notes: * average for fungicides or insecticides; ** average for substance group; *** study-specific value calculated by taking into account the specific types and quantities of pesticides used in apple production; **** The original values from [27] are increased by 20 MJ/kg a.i. in order to include the energy associated with packaging and transport.