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Energy Balance of Mallee Biomass Production in Western Australia

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Abstract

In Western Australia, mallee eucalypts are being developed to provide woody crops for wheatbelt farmers as part of a strategy to tackle a range of conservation issues including dryland salinity. If mallee crops prove commercially viable a considerable centrally-harvested biomass supply could be available for conversion to renewable energy and other industrial products. This study presents a systematic analysis of overall energy balance of mallee biomass production. Mallee biomass production achieves strong energy gain with an energy ratio (the ratio of total energy outputs and total non-renewable energy inputs) of 41.7. This ratio is considerably higher than those of other energy crops, e.g. approximately 7.0 for the production of rapeseed (as feedstock for biodiesel production) in Central Europe. Almost 80% of total energy inputs during mallee biomass production occur in biomass harvest and transport, arising mainly from the use of fossil fuels. To further improve the energy ratio, strategies should be focused on the optimisation of harvest and transport logistics, as well as the improvement of machinery fuel efficiency.

Introduction

Dryland salinity is a serious economic and environmental problem in the low to medium rainfall (300 – 600 mm mean annual rainfall) 'wheatbelt' agricultural areas of Australia [1-5] and leads to an estimated annual loss of about a billion dollars [3]. Increasing plant water use by adoption of perennial woody crops is a key strategy to manage dryland salinity [2-5]. In Western Australia (WA), several species of mallee eucalypts are being developed as woody crops. Some 11,000 ha (30 million trees) have been established by farmers across the wheatbelt over the past decade [2]. The successful large-scale implementation of mallee planting in WA requires two conditions be satisfied, *viz.* achieving the collateral benefits [3,5] and meeting farmers' commercial objectives [5,6]. There has been considerable R&D to stimulate progress in establishing a viable mallee-based industry [2,5,7-9], including the innovative "integrated processing" [7-9] to concurrently produce several products from mallee biomass.

Renewable fuels are becoming increasingly important for sustainable development of human society due to escalating energy demand, rapid depletion of fossil fuel reserves, serious environmental concerns related to fossil fuel use, and the desire for national energy security. Besides tackling dryland salinity mallee could supply renewable biomass fuels and feedstocks for industrial products. It has a short harvest cycle, can rapidly regenerate from coppice, has low production costs and is amenable to efficient large-scale supply chain (from harvest to central processor) development. Mallee biomass has the potential to become a fuel for base-load energy generation to complement declining use of fossil fuels.

There are three key factors that will determine the viability of mallee biomass as a resource for bioenergy and industrial products. The first is the economics of biomass production and utilisation. Recent feasibility investigation indicates that mallee should be a competitive biomass feedstock [5,9]. The second is its environmental performance as part of more sustainable agricultural systems. The third is its carbon and energy balances, which will determine whether it is a truly renewable resource. Yet little detailed work has been done so far on the third category of factors. This study conducts a systematic analysis of overall energy balance to evaluate the energy viability of the production of mallee biomass in WA.

Methodology

General considerations

The energy balance analysis is based on direct field practice for biomass production from mallee grown in the low to medium rainfall (300-600 mm mean annual rainfall) agricultural areas in WA. The assessment methodology used in this study is principally in accordance with the International Standard Organisation ISO 14040–14043 [10-13] on life cycle analysis. However, it should be noted that this work focuses only on the assessment of energy viability.

Mallee biomass production system

The full mallee production system considered in this study of overall energy balance is illustrated in Figure 1. The system is assumed to have a duration of 50 years, including an initial 5 years to first harvest followed by fifteen coppice harvest cycles, each having a duration of three years. After the 50 year period, the system is assumed to be terminated or re-established for a new 50 year period.

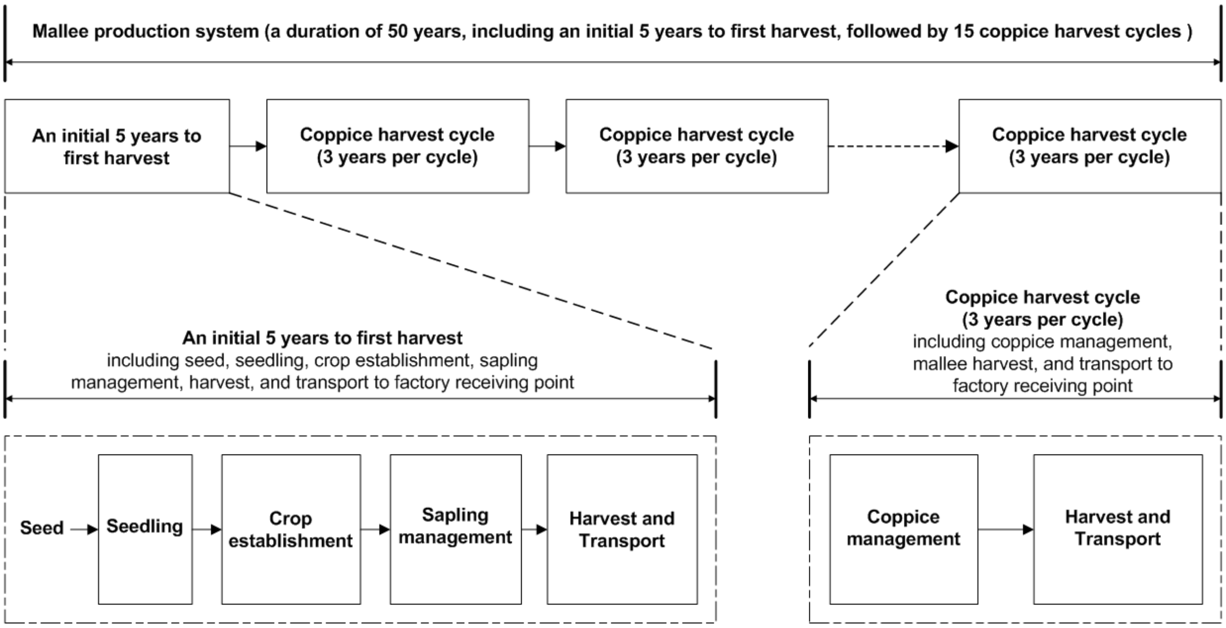


Figure 1 Mallee production system for biomass production

System modelling, energy inputs and outputs

The system modelling exhaustively accounts for all activities and/or processes which may involve direct energy inputs (diesel and petrol fuels, petroleum products, heat, electricity etc.) and/or indirect energy inputs (fertilisers, agrochemicals, tractors, agricultural machinery, transport equipment, labour, capital cost, etc.). The energy output is the energy contained in all mallee biomass components, i.e., wood, bark and twig, and leaf. All input and output parameters were converted to energy dimensions to enable direct comparison. Calculations are based on the total biomass quantity produced per hectare for the 50 year period. Therefore, in this study, the functional unit is *MJ per ha for a production period.*

Specific energy density

The specific energy density is defined as the total accumulated non-renewable primary energy accumulated in a unit quantity of an item. Whenever possible, the specific energy density of an item is calculated using Australian statistical data, direct first-hand process data, process analysis, or sample analysis. Otherwise, data published in the latest literature are considered.

Data on the accumulated primary energy in diesel and petrol fuels are from reference [14], taking into account the inherent energy value of the fuel, and a factor to account for accumulated energy for fuel production and delivery. Specific accumulated energy density of the manufacturing, maintenance and disposal of machinery (including harvesters, tractors, trucks and cars etc.) are adapted from the data in a previous publication [15]. Accumulated energy in NPK fertilisers and agrochemicals are taken from reference [16], taking into account energy in production, packaging and delivery. The capital costs were converted to an energy value using a dollars:energy conversion factor, according to the method used in [17]. Energy inputs due to other machinery operation costs and the use of labour were dealt with in a similar way. The conversion factor in these steps was calculated based on the latest Australian statistics on national total energy consumption and gross domestic product [18].

Energy ratio

Energy ratio (R) is defined as the ratio of the total energy embedded in the biomass products to the total non-renewable primary energy used during mallee biomass production, calculated as

$$R = \frac{Total \quad bio-energy \quad in \quad mallee \quad biomass}{Total \quad non-renewable \quad energy \quad used \quad during \quad biomass \quad production}$$

A renewable biomass production process requires R be greater than 1.

Results and Discussion

Energy inputs during mallee biomass production

Energy inputs during production of seedlings

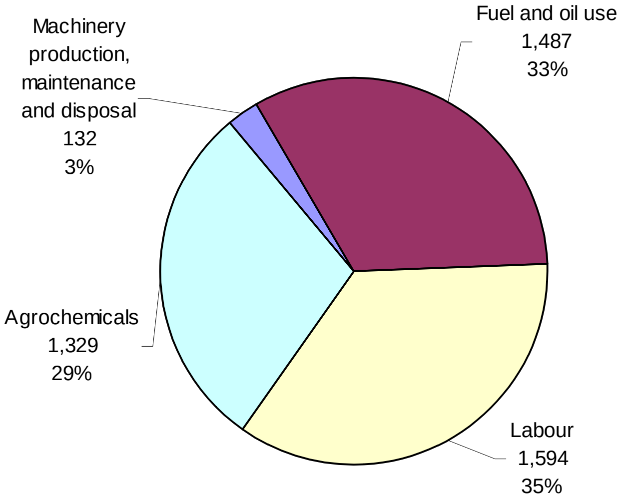
Specific energy embedded in genetically improved seed is estimated to be 0.28 MJ/seed, based on the conversion from monetary cost of seed production to an energy value. Field data show that approximately three seeds are needed to establish one successful seedling in the field. Seedling survival following planting is typically 90%, giving a plantation density of 2,400 surviving mallees per hectare. Under these conditions, the accumulated energy in seed is estimated to be 2,265 MJ per ha for a production period. The accumulated energy in seedlings is calculated based upon an analysis of a nursery with a production capacity of 25 million seedlings per year. The accumulated energy in a seedling is estimated to be 1.81 MJ/seedling, excluding the accumulated energy in the seed. For a planting density of 2,667 seedlings per hectare, the accumulated energy in seedlings is estimated to be 4,827 MJ per ha for a production period.

Energy inputs during crop establishment

Mallee crops need to be established once for each 50 year period, as illustrated in Figure 1. During this period each harvest takes all the above the ground biomass while the mallee root or ligno-tuber remains intact to give rise to the next coppice crop. Mallee crop establishment involves job scoping and site work. Job scoping includes site inspection, planning and initiation of operations, while site work includes land preparation and seedling planting.

Table 1 Energy inputs of various activities in mallee crop establishment

Crop establishment	MJ/ha for a production period	%
Job scoping		
Initialisation of task plan	45	1.0
Site inspection	165	3.6
Site work		
Site supervision	165	3.6
Contract markup and map	289	6.4
Farmer earth works	703	15.5
Sites mounding	53	1.2
Farmer weed control	1,417	31.2
Monitor mallee seedling production at nursery	25	0.5
Despatch seedlings to planting location	109	2.4
Hand planting by contractor	1,572	34.6
Total	**4,542**	**100.0**

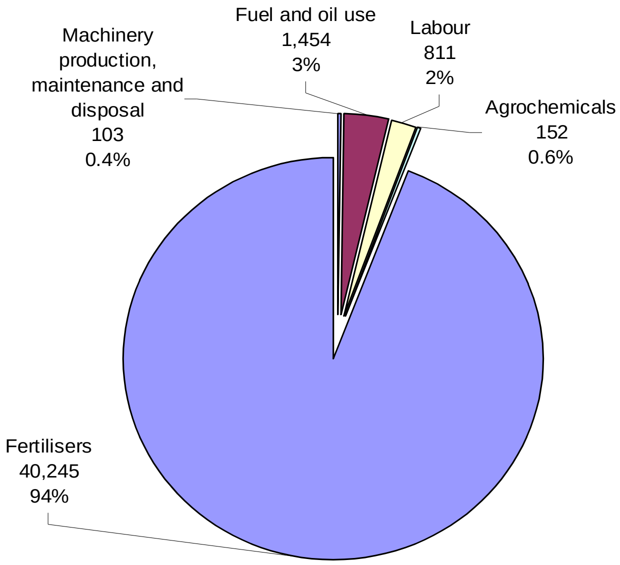


Unit: MJ/ha for a production period
Total energy input: 4,542 MJ/ha for a production period

Figure 2 Energy consumption in crop establishment

Table 2 Energy inputs of various activities in sapling and coppice management

Sapling and coppice management	MJ/ha for a production period	%
Post plant contingencies (sapling management only)		
Monitoring young planted seedlings	1,169	2.7
Post plant or coppice contingencies (during both sapling and coppice management)		
25% probability of need for follow-up weed control	185	0.4
5% probability of need for insect control	26	0.1
Fertiliser applications	1,139	2.7
DAP	10,734	25.1
UREA	27,769	64.9
Muriate of Potash	1,742	4.1
Total	**42,765**	**100.0**



Unit: MJ/ha for a production period
Total energy input: 42,765 MJ/ha for a production period

Figure 3 Energy consumption in crop management

Table 1 lists the detailed energy inputs for crop establishment, indicating a total energy input of 4,542 MJ/ha for a production period. Most energy is consumed in site work, dominantly by three activities, i.e., farmer earth works, farmer weed control and hand planting by contractor, accounting for 15.5, 31.2, and 34.6% of the total energy input, respectively. Data in Figure 2 further indicate that energy inputs are dominated by agrochemicals, labour, fuel and oil for machinery operations.

Energy inputs during sapling management and coppice management

As shown in Figure 1, sapling management is necessary during the initial 5 years to first harvest while coppice management is necessary during each coppice harvest cycle. The main activities of sapling and/or coppice management are tending post planting or coppice contingencies and supply of NPK fertilisers. It is assumed that only modest fertiliser inputs will be required because mallee crops are planted in belts designed to capture surplus water and nutrients from the adjacent annual crops and pastures. Research has commenced to define appropriate fertiliser regimes. It can be seen in Table 2 that a total energy input of 42,765 MJ/ha is needed in the 50 year period, including one sapling management cycle in the initial five years to first harvest and fifteen coppice management cycles for the subsequent fifteen coppice harvest cycles. Data in Figure 3 indicate that energy consumption is dominated by application of fertilisers, which accounts for about 94% of the total energy input.

Energy inputs during harvest and transport

Conventional forestry supply chains are fundamentally unsuited to the economic requirements of Australian short cycle tree crops [9]. These new tree crops require the development of a supply chain capable of efficiently handling the range native Australian tree species employed, and suited to Australian transport conditions.

A design description of a supply chain that should provide the required level of economic efficiency has been presented in another report [9]. Figure 4 illustrates this conceptual biomass supply chain, and based upon this design, a detailed analysis of the energy balance during biomass harvest and transport was conducted. In this supply chain, a continuously travelling harvester will be employed to harvest and chip biomass directly into haulouts. The haulouts, which will be large bulk bins towed by tractors, will transfer the biomass approximately 1 km from the harvester to road transport trailers and load the road trailers. The road trailers will be configured in pairs and moved in rotation by a single prime mover. The biomass will be transported to the factory receiving point over an average distance of 70 km. The supply chain design is optimised for the anticipated biomass flow rate so that on-farm stockpiles are eliminated, apart from the accumulation of biomass in the fleet of road trailers, and there is little delay in loading and unloading.

As shown in Figure 5, the energy inputs during biomass harvest are significant, being 106,400 MJ per ha for a production period. The high energy consumption is predominantly due to the use of diesel fuel during the operation of the harvester and haulouts, with fuel contributing almost 70% of the total energy consumption for harvest and hauling out.

Figure 6 presents the energy inputs during mallee biomass transport. The total energy input is also significant, being 86,630 MJ per ha for a production period. Similar to the harvest process, the majority of energy consumption is due to the use of fossil fuels during transport, accounting for almost 80% of the total energy consumption. Therefore, optimisation of harvest and transport logistics, and improvement in fuel efficiency of machinery operations may offer further improvement of the overall efficiency of biomass harvest and transport.

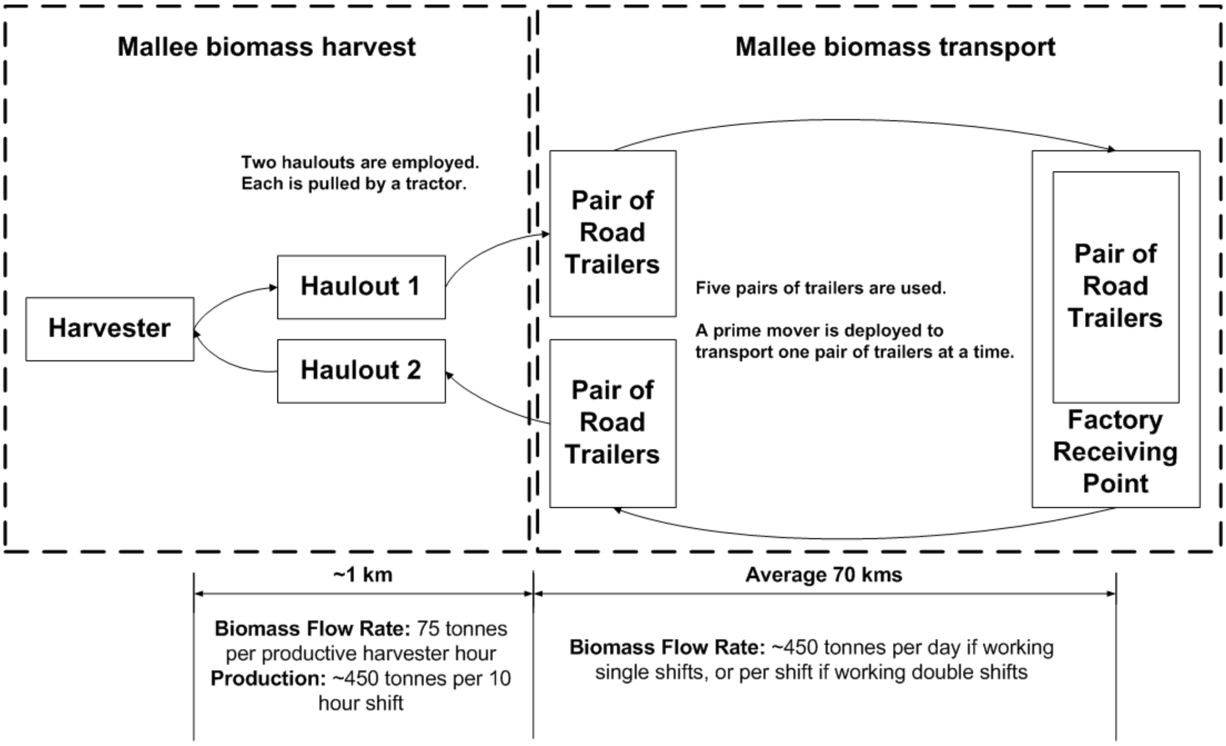


Figure 4 A conceptual woody biomass supply chain [9]

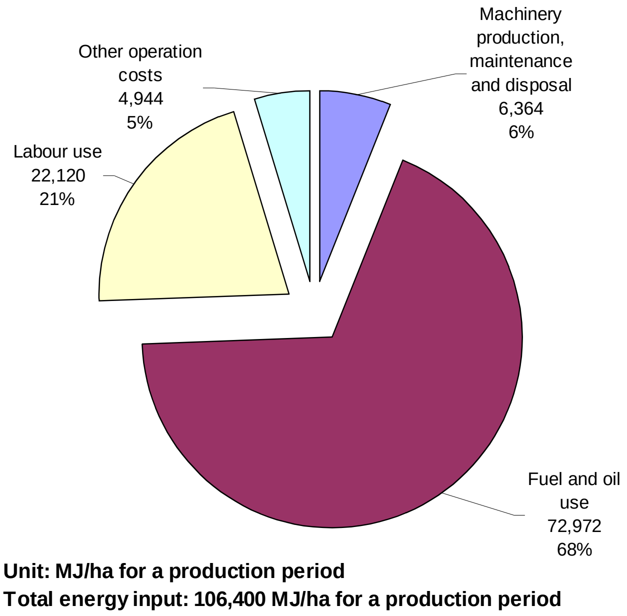


Figure 5 Energy consumption during mallee biomass harvest

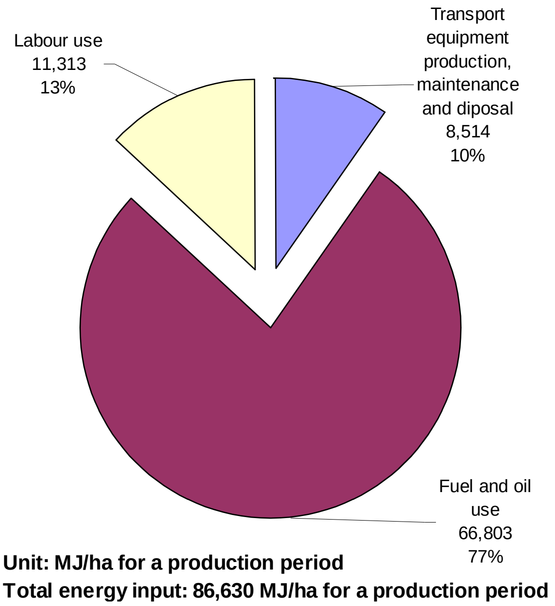


Figure 6 Energy consumption during mallee biomass transport

Table 3 Overall energy balance

Energy Input	**Total (MJ/ha for a production period)**	**%**
Seed	2,265	0.9
Seedling	4,827	2.0
Crop establishment	4,543	1.8
Sapling and coppice management	42,765	17.3
Harvest	106,400	43.0
Biomass transport	86,630	35.0
Total Energy Input	**247,429**	**100.0**
Energy Output		
Wood	3,971,463	38.5
Bark	2,681,499	26.0
Leaf	3,655,131	35.5
Total Energy output	**10,308,093**	**100.0**
Energy Ratio (*R*)		**41.7**

Table 4 Breakdown of energy inputs

Energy Input	**Total (MJ/ha for a production period)**	**%**
Seed	2,265	0.9
Seedling	4,827	2.0
Machinery production, maintenance and disposal	15,112	6.1
Fuel and oil use	142,716	57.7
Other operation costs	4,944	2.0
Labour	35,839	14.5
Agrochemicals	1,481	0.5
Fertilisers	40,245	16.3
Total Energy Input	**247,429**	**100.0**

Energy outputs in mallee biomass production

Mallee crops planted in WA are not yet old enough to have demonstrated sustainable coppice yields. It is clear that yield will strongly depend on total available water, including rainfall, and capture of water in addition to rainfall. The major reason why mallee crops are grown in belt configurations is to facilitate capture of additional water from the surplus in the adjacent annual crop or pasture. In reference [5] a model is presented that predicts yield, subject to availability of water, and profitability in relation to alternative crops. This model indicates an average yield of 93 green tonnes per hectare per harvest cycle will be required in the wheatbelt of WA for mallees to be economically competitive with the alternative crops, and that there is sufficient available water to achieve such yield on a planted area of 3.7% of all farmland. However, preliminary empirical data indicate yields of about half this level. Many factors may explain why current yield appears to be less than predicted, for example, wider belt width in planted stands, the recent period of lower than average rainfall, sub-optimal planting layout and site selection. A mallee yield of 60 green tonnes per harvest cycle, intermediate between the predicted and observed levels, was therefore chosen for the estimate of energy output. If yield is less than 60 green tonnes on a three year harvest cycle then it is likely that harvest frequency would have to be reduced to maintain harvest efficiency. Mallee biomass consists of wood (40%), bark and twig (25%) and leaf (35%), which have similar moisture contents (45%) and energy contents of 19.5, 19.5 and 21.2 MJ/kg (db), respectively [7]. Based on these data, the total energy output is estimated to be 10,308,093 MJ/ha over the full 50 year period, as shown in Table 3.

Overall energy balance of mallee biomass production

The overall energy balance of mallee biomass production is listed in Table 3. Under the assumptions used in this study, mallee biomass production achieved an energy ratio of 41.7, significantly higher than other energy crops, e.g. rapeseed production in Central Europe (with an energy ratio of 7.0 [19]). This high ratio arises mainly from the strong coppicing ability of mallee, that avoids regular replanting inputs, and the complementary position mallee occupies with annual agricultural crops, that generates high mallee yields through providing surplus water and nutrients. It could be argued that the energy ratio determination should be applied to the whole system, not just the highly energy efficient mallee component. However, mallee is a new enterprise and should also be evaluated separately to confirm its viability.

Table 3 also indicates that almost 80% of energy consumption during mallee biomass production is due to harvest (43.0%) and transport (35.0%). Table 4 further indicates that almost 60% of the total energy consumption is due to the use of diesel fuel for machinery operations, particularly during harvest and transport. The results clearly indicate that to further improve energy ratio, strategies should be developed to optimise harvest and transport logistics and to improve the fuel efficiency of machinery operations.

Conclusion

This study presents a systematic analysis of overall energy balance during mallee biomass production. Mallee biomass achieves an energy ratio of 41.7, substantially higher than other crops such as rapeseed production in Central Europe (with an energy ratio of 7.0), demonstrating strong energy gain. As almost 80% of energy consumption is due to biomass harvest and transport (particularly the use of fossil fuels for machinery operations), to further improve the energy ratio, future development should optimise harvest and transport logistics and improve machinery fuel efficiency.

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