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Research article

# Forecasting model based on morphological characteristics for yield of konjac (*Amorphophallus muelleri* Blume) planted in Tak province, Thailand

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## Abstract

**Importance of the work**: The useful part of konjac (*Amorphophallus muelleri* Blume) is its tuber; however, it is difficult to estimate its annual production without weighing the tubers. The newly developed forecasting model aims to provide valuable insights and support decision-making processes related to productivity management, marketing and crop planning.

**Objectives**: To study the relationship between konjac tuber weight and vegetative morphological factors.

**Materials & Methods**: Data were collected from 163 individual konjac plants growing in sample plots. The vegetative morphological factors measured were: stem diameter at ground level, stem height, length of the longest leaf, crown cover, number of bulbils, tuber diameter and tuber weight. A model was developed to forecast konjac productivity using stepwise multivariate regression.

**Results**: The study identified correlations between the vegetative morphological factors of *A. muelleri*, with the stem diameter at ground level ($D_0$) being the most reliable factor. The equation used to predict *A. muelleri* tuber weight (Y) was $\log Y = -3.34 + 2.17 \log D_0$, which had a high coefficient of determination (0.95, $p < 0.01$). However, this equation was specific to *A. muelleri* productivity in Tak province.

**Main finding**: The developed equation should be valuable for tuber weight estimation without the need for tuber extraction. It should assist stakeholders to meet market demand.

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## Introduction

Non-timber forest products (NTFPs) have important economic and social value, serving as raw materials for countless products including fiber, tannin, bark and products derived from plants and animals (Husen et al., 2021). They are important sources of food, health and energy for rural populations (Zamora and Avila-Foucat, 2020). NTFPs, which are used in medicine, cosmetics, and local cultural practises (Cavendish, 2000; Chamberlain and Prednyb, 2004), are vital to subsistence and commercial agriculture (Liu and Moe, 2016; Lepcha et al., 2022). However, the ecological and economic importance of NTFPs is seldom integrated with forest management. A lack of NTFP management may decrease the diversity and sustainability of forests, adversely affecting the livelihoods of local communities (Talukdar et al., 2021). Thus, it is vital to manage and promote the sustainable use of NTFPs (Uprety et al., 2016; Zhang et al., 2021). In many developing countries, NTFPs, such as those derived from konjac, are used as prime raw materials and exported in large volumes (Husen et al., 2021).

Konjac (*Amorphophallus muelleri* Blume) is a perennial tuberous plant from the family Araceae with origins in Africa and the tropical and temperate regions of Asia and primarily used for food and medicine (Hetterscheid and Ittenbach, 1996). There are no records of its distribution in the tropical regions of the Americas, while in Asia, konjac is found throughout many countries, including India, Bangladesh, Myanmar, Japan, Laos, Thailand, Malaysia, Indonesia and the Philippines (Hetterscheid, 2006). In Thailand, konjac grows in natural forests from the western border provinces of Mae Hong Son, Chiang Mai, Tak, Kanchanaburi and Ranong to the southern province of Nakhon Sri Thammarat (Hetterscheid and Ittenbach, 1996). Currently, konjac is being promoted in Thailand, in particular in Tak province, for planting alongside forest plantations and on agricultural farms. It has produced high economic returns due to a constituent fiber called glucomannan, which is used as a starch substitute in various food products and in the medical field in dietary supplements for weight loss and to lower cholesterol (Keithley et al., 2013). Most related research has focused on its use in food processing (Al-Ghazzewi et al., 2015; Gómez et al., 2017; Ni et al., 2021; Jiang et al., 2022; Wang et al., 2022; You et al., 2022; Zhang and Rhim, 2022) and the pharmaceutical industries (Tester and Al-Ghazzewi, 2016; Du et al., 2019; Mohammadpour et al., 2020; Wu et al., 2022; Zhou et al., 2022). Other applications include mixing konjac gel with coal to prevent spontaneous combustion (Wang et al., 2021). Still, other researchers have focused on the environmental aspects of konjac (Douglas et al., 2015; Qin et al., 2019).

There have been multiple assessments of tuber weight or productivity (Douglas et al., 2005). The study of konjac management, harvesting and productivity is complicated by the fact that glucomannan is only found in the underground tuber; thus, tools are needed to improve forecasting tuber productivity before the tubers are extracted (Budiman and Arisoesilaningsih, 2012; Chamberlain et al., 2013; Chan et al., 2013; Zhang et al., 2015; Liu et al., 2016; Ei et al., 2017; Zhang et al., 2017; Gomes et al., 2021). In Thailand, research on konjac plants with ovoid tubers (Napiroon et al., 2013) has mostly focused on applications in the food processing industry (Wattanaprasert et al., 2013; Mekkerdchoo et al., 2016; Sorapukdee et al., 2019). Despite the economic importance of konjac, uncertainty caused by a lack of effective yield forecasts impacts production planning, optimization and sales. This has contributed to unpredictability in the quantity of konjac generated.

The current study developed a model for forecasting tuber weight in Jor Kee village, Tha Song Yang district, Tak province, Thailand, where villagers grow the plant commercially (Mianmit et al., 2019). The aim was to apply the forecasting model to help in productivity management, marketing, purchase planning and supporting local communities in crop planning to meet market demand.

## Materials and Methods

### *Study area*

The study area was the village of Jor Kee, Moo 6, Mae La subdistrict, Tha Song Yang district, Tak province, Thailand (17° 11′ 26″ N, 98° 19′ 44″ E; Fig. 1) and consisted of seven survey points, as listed in Table 1. The village covers approximately 719 ha, comprising mostly forests and steep-sloped mountains with elevations in the range 720–1,200 m above mean sea level. In 2021, the local climatic data in Mae Sot district, Tak province indicated an annual rainfall of 1,889 mm, with the highest rainfall measured in July (24.4 mm/d). The maximum, minimum and average temperatures were approximately 40°C, 11.5°C, and 27.7°C, respectively (Thai Meteorological Department, 2021).

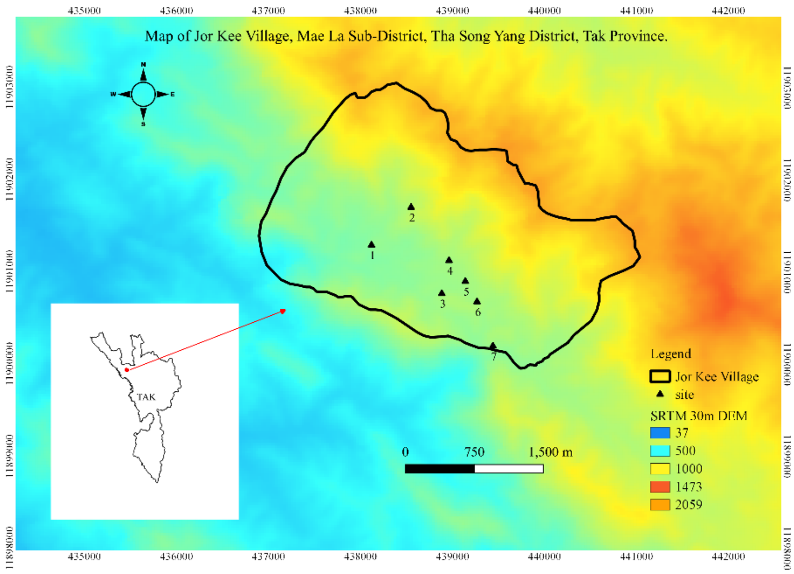


**Fig. 1** Location of the village of Jor Kee, Moo 6, Mae La subdistrict, Tha Song Yang district, Tak province, Thailand (data sourced from Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) at a scale of 30 m

**Table 1** Location of survey points in Universal Transverse Mercator (UTM) coordinates, topography, the land use classification

| Point number | Coordinates UTM Zone47N | | Elevation (meters above mean sea level) | Number of tubers | Land use |
|---|---|---|---|---|---|
| | X | Y | | | |
| 1 | 438117 | 1901290 | 725 | 18 | Residential area |
| 2 | 438547 | 1901699 | 827 | 33 | Under trees in shifting cultivation (swidden plots) |
| 3 | 438881 | 1900764 | 778 | 5 | Alongside on-farm crops in monoculture (corn) |
| 4 | 438960 | 1901123 | 778 | 16 | Residential area |
| 5 | 439137 | 1900897 | 779 | 33 | Alongside on-farm crops in monoculture (corn) |
| 6 | 439264 | 1900675 | 787 | 21 | Alongside on-farm crops in monoculture (corn) |
| 7 | 439437 | 1900195 | 760 | 37 | Alongside on-farm crops in monoculture (corn) |

## *Data collection*

*A. muelleri* in Jor Kee village was not planted systematically; rather, cultivation occurred in any available space near the residents' houses, on farms and in swidden plots. Therefore, data collection commenced with a survey on foot to determine the boundaries and locations of konjac plots, to which were assigned 23 unique sampling numbers. Then a simple random plot sampling design was applied to draw seven plots for the present analysis. Data were collected from 163 individual konjac plants growing in the sample plots. The mean ± SD of the stem diameters at ground level was 2.10 ± 1.12 cm. These values were used to estimate an appropriate sample size (*n*) of at least 102 konjac plants with a 51% coefficient of variation (CV) in their stem diameter at ground level. This sample size was calculated based on Shiver and Borders (1996) using the formula $n = t^2 \times CV^2 / AE^2$ (where $n$ is the sample size, t = 1.96 at the 95% confidence interval, CV = 51%, and AE is the acceptable level of error at 10%). In 2021, data collection from the konjac sample plots occurred in September, when the plants were mature and the villagers were beginning to harvest tubers for sale. As shown in Fig. 2, data collected consisted of stem height (H), stem diameter at ground level ($D_0$), length of the longest leaf (Ll), tuber diameter (Td), crown cover (Cr), bulbils (B), tuber weight (Tw) and the total number of leaves (Ln), according to Budiman and Arisoesilaningsih (2012) and Ei et al. (2017).

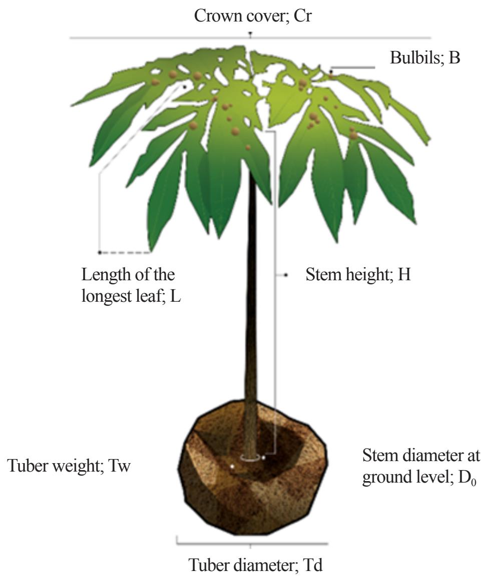


**Fig. 2** *Amorphophallus muelleri* morphological factors and data considered for tuber weight forecasting model

### *Data analysis*

One-way analysis of variance was used to determine the differences among growing sites. Pearson's correlation coefficient (r) was calculated to determine any significant relationships between the various factors and tuber weight, where r was in the range between -1 and +1, with a negative value indicating a negative correlation, a positive value indicating a positive correlation and values close to zero indicating no relationship. The r values were presented in terms of the strength level of the relationship as proposed by Cohen (1988) with low (r = 0.10–0.29), medium (r = 0.30–0.49), and high (r = 0.50–1.0) levels. All factors having a significant linear relationship with tuber weight were included in the prediction model for konjac productivity. Stepwise multiple regression and residual analysis were applied for the linear model fitting and validation. The model with the best fit was chosen to predict the konjac tuber weight based on a set of statistical values: F at a significance level of 0.05 ($p < 0.05$), the maximum coefficient of determination ($R^2$) and the minimum standard error of the estimate (SE), according to Budiman and Arisoesilaningsih (2012) and Ei et al. (2017).

## Results

### *General information regarding A. muelleri in the study area*

The data on *A. muelleri* in Tak province showed that the species was cultivated at altitudes between 300 and 800 m above mean sea level. Local climate data was obtained from the Thai Meteorological Department, in Mae Sot District, Tak Province (Thai Meteorological Department, 2021) at a latitude of 16°42'09''N and longitude of 98°32'30''E, approximately 71 km from the study area. The average temperature around the site was 27°C with the maximum temperature reaching around 40°C, while the minimum temperature was around 11.5°C. The area received an average annual rainfall of 1,889 mm, with the average relative humidity being around 80%. The konjac crop performed better in soil where the groundwater depth exceeded 50 cm during the rainy season. The best soil for cultivation was a sandy loam or a well-drained, loamy clay soil with a high organic matter content (>3%) and a pH in the range 5.5–7.0. *A. muelleri* is indigenous to heavily shaded sites and is most productive at 175–250 calories/cm$^2$/day of solar radiation (Protected Area Regional Office 14 Tak Province, 2018).

Based on the collected data and filed observations, *A. muelleri* grows from an underground tuber during the late spring to early rainy season, around the end of April. The plant turns brown and dies back during the late rainy to early cool season, around the start of November. Konjac self-propagates; its leaves contain 1–41 bulbils per plant or an average of 5.83 bulbils per plant. When a bulbil falls to the ground, it grows roots and may become a new plant. The bulbils of the leaves from the middle of the stem are larger than those from other locations.

The locals grow konjac in any available space, even under trees, with no specific planting patterns. Konjac was found in patches resulting from the natural reproductive tendency for bulbils to fall and grow near the maternal plant. Farmers tend plants only during the first years of the plants, then let them self-propagate and multiply before eventually harvesting and selling tubers that have reached a weight greater than 500 g.

Farmers pull konjac tubers from the ground to determine whether they have reached selling weight. If a tuber weighs less than 500 g, it is either replanted or sold to others to use as seed stock for growing konjac. Harvesting generally takes place in October, when the plant is approaching maturity and tubers are at their largest. Processing factories also begin to purchase tubers around this time; farmers may sell tubers to the factories directly or through intermediaries, who are usually locals. The intermediaries collect the tubers and place them in dry, well-ventilated storage before selling them to factories when the expected price (usually THB 12–28/kg or US$ 0.375–0.875/kg) is met. Then, the factories process the tubers into dried tubers, powder, noodles and other products that are sold both nationally and internationally. Vegetarian food processing factories and supermarkets in Chiang Mai, Thailand are among the top domestic customers, while China and Japan are the preferred international markets (Fig. 3).

### *Vegetative morphological factors of A. muelleri samples*

The results of the morphological study of 163 *A. muelleri* plants are summarized in Table 2. Mean ± SD values were: stem diameter, 2.10 ± 1.12 cm; stem height, 74.51 ± 29.75 cm; crown cover, 56.06 ± 21.74 cm; longest leaf, 34.99 ± 13.90 cm; bulbils, 5.81 ± 6.64; total number of leaves, 22.85 ± 18.57; and tuber weight, 480.65 ± 570.59 g.

**Table 2** Mean, maximum, minimum and SD for vegetative morphological factors of *Amorphophallus muelleri*

| Konjac data ($n$ = 163) | Maximum | Minimum | Mean | SD |
|---|---|---|---|---|
| $D_0$ (cm) | 5.53 | 0.05 | 2.10 | 1.12 |
| H (cm) | 145.90 | 12.01 | 74.51 | 29.75 |
| Cr (cm) | 122.50 | 15.70 | 56.06 | 21.74 |
| $L_1$ (cm) | 69.10 | 9.80 | 34.99 | 13.90 |
| B (n) | 41 | 1 | 5.81 | 6.64 |
| $L_n$ (n) | 104 | 5 | 22.85 | 18.57 |
| Tw (g) | 2,948 | 12 | 480.65 | 570.59 |

$D_0$ = stem diameter at ground level; H = stem height; Cr = crown cover; Ll = length of longest leaf; B = number of bulbils; Ln = total number of leaves; Tw = tuber weight.

### *Relationships between planting sites and growth and morphology of A. muelleri*

The *A. muelleri* had been planted on three main types of site: near houses, alongside crops in monoculture farmlands, and under trees in swidden plots. Regardless of the site, nearly all farmers left their konjac to grow naturally without fertilizers or pesticides. Farmers appeared to believe that *A. muelleri* would die if fertilizers or pesticides were applied. The stem diameter at ground level ($p$ = 0.144), stem height ($p$ = 0.212), length of the longest leaf ($p$ = 0.213), crown cover ($p$ = 0.410) and number of bulbils ($p$ =0.218) were not significantly different among the three types of sites. *A. muelleri* has been reported to grow well on sites with ranges in temperature of 20–35°C, elevation of 300–800 m and slope of 5–10°, with the latter preventing standing water (Protected Area Regional Office 14 Tak Province, 2018). As the sampling sites in the current study satisfied these conditions, the resulting konjac growth and morphological data were suitable for developing a forecasting model.

### *Correlations between vegetative morphological factors of A. muelleri*

Correlations between the vegetative morphological factors were tested for: stem diameter at ground level ($D_0$); height (H); crown cover (Cr); longest leaf (L1); number of bulbils (B); and total number of leaves (Ln). The results are shown in Table 3.

All variables were significantly positively related, as defined by Cohen (1988), with r values greater than 0.50. The strongest relationship was between stem diameter at ground level and crown cover (r = 0.90). Height and number of bulbils had the weakest relationship (r = 0.51). Some of the independent variables had highly significant ($p < 0.01$) relationships with multicollinearity; therefore, both easy to measure and highly correlated variables were selected for the productivity forecasting model.

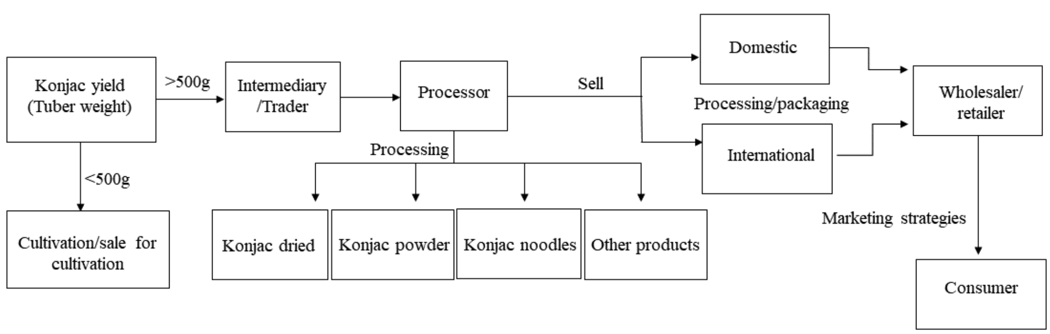


**Fig. 3** Marketing chain for *Amorphophallus muelleri*

**Table 3** Correlation between vegetative morphological factors of *Amorphophallus muelleri*

| Konjac data ($n$ = 163) | $D_0$ | H | Cr | Ll | B | Ln |
|---|---|---|---|---|---|---|
| $D_0$ | 1 | 0.77** | 0.90** | 0.89** | 0.69** | 0.86** |
| H | 0.77** | 1 | 0.83** | 0.81** | 0.51** | 0.66** |
| Cr | 0.90** | 0.83** | 1 | 0.93** | 0.60** | 0.78** |
| L1 | 0.89** | 0.81** | 0.93** | 1 | 0.61** | 0.77** |
| B | 0.69** | 0.51** | 0.60** | 0.61** | 1 | 0.81** |
| Ln | 0.86** | 0.66** | 0.78** | 0.77** | 0.81** | 1 |

$D_0$ = stem diameter at ground level (cm); H = stem height (cm); Cr = crown cover; Ll = length of longest leaf (cm); B = number of bulbils; Ln = total number of leaves (n).
** = highly significant at 99% level ($p < 0.01$).

### *Correlations between vegetative morphological factors and tuber weight*

Stem diameter at ground level, height, crown size, longest leaf, number of bulbils and total number of leaves were highly significantly ($p < 0.01$) related to konjac productivity, as indicated in Table 4. All independent variables were significantly positively related to konjac productivity, as defined by Cohen (1988), with r values greater than 0.50.

Stem diameter at ground level was strongly correlated with tuber weight (r = 0.91), whereas height had the weakest correlation (r = 0.63). These results indicated that of the observed vegetative morphological factors, stem diameter was the best predictor of konjac yield.

**Table 4** Pearson's correlation coefficient (r) values between vegetative morphological factors of *Amorphophallus muelleri*

| Vegetative morphological factor | R |
|---|---|
| $D_0$ | 0.91** |
| H | 0.63** |
| Cr | 0.77** |
| Ll | 0.75** |
| B | 0.68** |
| Ln | 0.79** |

$D_0$ = stem diameter at ground level (cm); H = stem height (cm); Cr = crown cover; Ll = length of longest leaf (cm); B = number of bulbils; Ln = the total number of leaves.
** = highly significant at 99% level ($p < 0.01$).

### *Model for forecasting konjac yield*

As indicated in Table 3, all *A. muelleri* vegetative morphological factors were correlated with one another. Therefore, the forecasting model could contain all or only one of the factors. However, an ideal model should include variables that are both easy to measure on-site and accurate in predicting productivity. Table 4 shows that stem diameter at ground level best satisfied these conditions. The forecasting model for konjac yield is presented in Table 5 ($R^2 = 0.95$, $p < 0.01$) and Fig. 4. This forecasting model for tuber weight has not been fully validated; only residual analysis was applied in this paper to confirm its accuracy. The residual plot in Fig. 5 shows no evidence of curvilinearity or heteroscedasticity. Thus, it was accepted that the linear model was appropriate. However, in the future, any developed tuber weight model should undergo comprehensive validation before implementation.

This forecasting model should help konjac farmers to estimate the underground yield (tuber weight) by measuring the stem diameter at ground level, eliminating the need to destructively harvest tubers. In addition, it could help to promote konjac cultivation as an additional source of income. The minimum and maximum weights of *A. muelleri* tubers, as predicted by the model, were 12 g and 2,948 g, respectively, which were consistent with data collected in the field.

**Table 5** Comparison of model constructed in current study with other reports of tuber weight of konjac

| Site | Species | MAP (mm) | MAT (°C) | Regression | $R^2$ | References |
|---|---|---|---|---|---|---|
| East Java, Indonesia | *Amormphophallus muelleri* | 2,680 | 27.7 | Log Y = 1.091 log $D_0$ + 0.765 log B** | 0.99 | Budiman and Arisoesilaningsih (2012) |
| Bago, Myanmar | *Amorphophallus bulbifer* | 2,300 | 26.0 | Log Y = –2.50 + 2.47 log $D_0$** | 0.92 | Ei et al. (2017) |
| Tak, Thailand | *Amormphophallus muelleri* | 1,900 | 29.5 | Log Y = –3.34 + 2.17 log $D_0$** | 0.95 | Current study |

Y = tuber weight; $D_0$ = stem diameter at ground level; B = number of bulbils; MAP = mean annual precipitation; MAT = mean annual temperature; $R^2$ = coefficient of determination.
** = significant ($p < 0.01$).

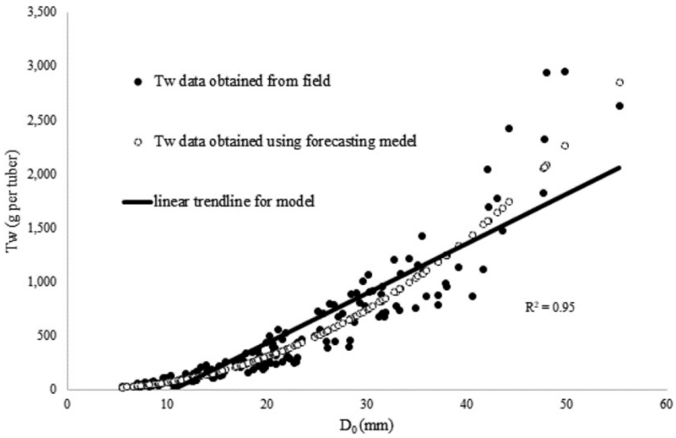


**Fig. 4** Scatter plot of relationship between natural logarithm of stem diameter at ground level ($D_0$) and tuber weight (Tw), where solid straight line indicates trend line for relationship

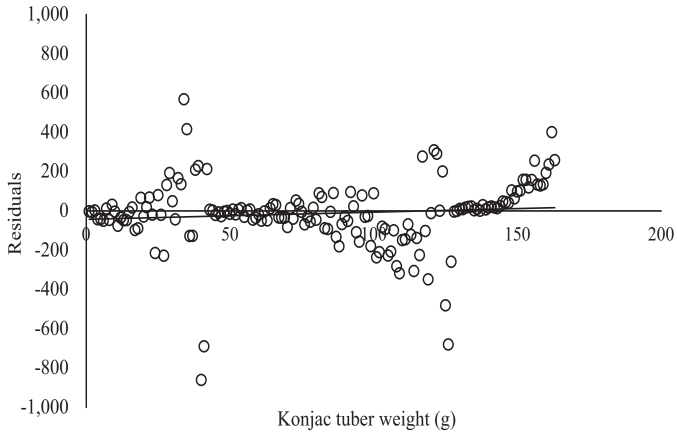


**Fig. 5** Residuals for tuber weight of *Amorphophallus muelleri*

## Discussion

A comparison of the linear regression equation obtained in the current study with that obtained by Budiman and Arisoesilaningsih (2012) in an agroforestry site of *A. muelleri* in Indonesia is presented in Table 5, with the Indonesian study also determining that stem diameter at ground level was the most influential factor in predicting tuber weight. Likewise, a model proposed by Ei et al. (2017) estimating the underground biomass of A. *bulbifer* reported that stem diameter at ground level was most strongly correlated with tuber weight. The phenological and morphological characteristics for six species of konjac reported by Jaleel et al. (2012) for stems growing out of a tuber. Ei et al. (2017) found that *A. muelleri* shed its stems during the dry season and grew new ones in the rainy season, while large A. *bulbifer* tubers could usually be collected from plants exhibiting vigorous stem growth, as evidenced by stem diameter. In accordance with the study of Indriyani et al. (2011), the current study data showed that a higher stem diameter resulted in a higher tuber diameter.

The mean stem diameter at ground level and the stem height listed in Table 2 were in similar ranges to those reported by Napiroon et al. (2013) for A. *bulbifer* (3.1 ± 1.74 cm and 89 ± 36.93 cm, respectively); in addition, Ei et al. (2017) report that the A. *bulbifer* tuber weight was 733.70 ± 1,071.52 g. Thus, it could be concluded that on average, the aboveground parts of these two species were similar, although the underground parts were different. Similar to the current study, Ei et al. (2017) found that the tuber weight had a relatively high SD. This result also corresponded with that of Chamberlain et al. (2013), who reported that their high SD for tuber weight was due to variations in plant response to underground conditions relative to responses to aboveground conditions. In addition, Indriyani et al. (2011) reported that the main factor affecting the aboveground stem diameter was the cation exchange capacity of the soil. However, none of these factors were used to directly predict tuber weight, suggesting that other factors are likely involved.

Indriyani et al. (2011) included other environmental factors that affected konjac productivity in their forecasting model, such as elevation, vegetation, climate and soil conditions. They found that the bulbils had the strongest influence in a model that predicted konjac productivity. The current study isolated a different set of independent variables from the study in Indonesia (Budiman and Arisoesilaningsih, 2012). Tuber weight can vary with environmental factors such as elevation, light intensity, age, soil calcium content, monthly temperature, annual rainfall, spacing density, crown cover percentage, the species of neighboring trees and tuber size on initial planting (Cohen, 1998; Budiman and Arisoesilaningsih, 2012; Douglas et al., 2015). Consequently, different independent variables at each site might influence the final tuber weight.

Notably, Budiman and Arisoesilaningsih (2012) conducted their study in an agroforestry system, whereas Ei et al. (2017) focused on areas practicing traditional swidden agriculture. In addition, the life cycle of konjac is complex and involves annual death and re-germination of the stem. Because konjac is a perennial plant that can be propagated naturally from foliar roots, its growth should be monitored regularly. Furthermore, the pattern of planting may influence growth.

The current study conducted in Tak province revealed that *A. muelleri*) crop cultivated by the local farmers was a minor source of income, with the farmers in the region growing konjac in any available space, including areas under trees, without following specific planting patterns. The konjac plants were found to grow in patches, which was a result of the natural reproductive tendency of bulbils to fall and germinate near the parent plant. This natural regeneration process has contributed to the spread of konjac in the region. Additionally, the ability of konjac to grow under trees makes it a suitable choice for forest regeneration efforts. The current study determined that the stem diameter at ground level was a significant factor in predicting the productivity of the konjac crop, suggesting that larger stem diameters are associated with higher productivity levels.

The developed forecasting model should help konjac farmers to estimate the underground yield (tuber weight) by measuring the stem diameter at ground level, which would eliminate the need to prematurely harvest some tubers. The model could also help to promote konjac cultivation as an additional source of income. The minimum and maximum weights of *A. muelleri* tubers, as predicted by the model were 12 g and 2,948 g, respectively, which were consistent with the data collected in the field. The forecasting model for konjac productivity in the future should undergo validation before implementation; The current study represents only the preliminary stage of konjac productivity model development.

Overall, the forecasting model could provide valuable insights and support decision-making processes related to productivity management, marketing, purchase planning and crop planning. Leveraging this knowledge should help stakeholders to work towards meeting market demand, while maximizing the potential of konjac cultivation in the region.

## Conflict of Interest

The authors declare that there are no conflicts of interest.

## Acknowledgements

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